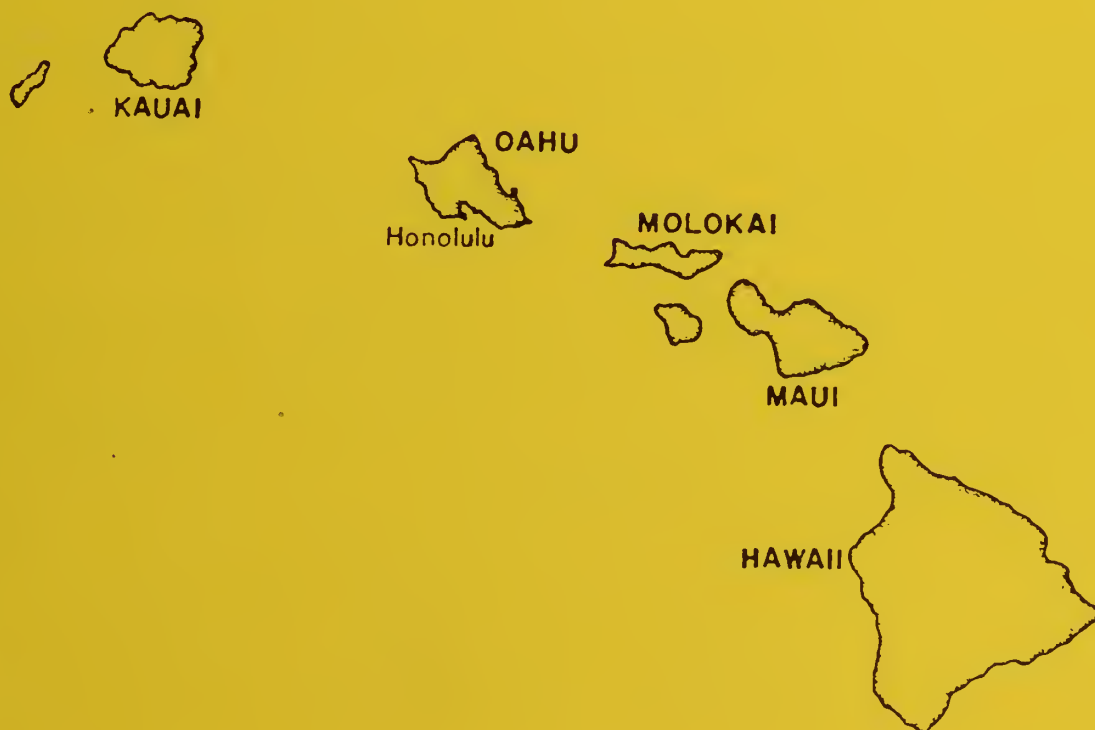


FWS/OBS-78/18

October 1978

Stream Channel Modification in Hawaii.
Part C: Tolerance of Native Stream Species
to Observed Levels of Environmental Variability



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To gather, analyze, and present information that will aid decision-makers in the identification and resolution of problems associated with major changes in land and water use.

To provide better ecological information and evaluation for Department of Interior development programs, such as those relating to energy development.

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FWS/OBS-78/18
October 1978

STREAM CHANNEL MODIFICATION IN HAWAII
PART C: TOLERANCE OF NATIVE STREAM SPECIES TO
OBSERVED LEVELS OF ENVIRONMENTAL VARIABILITY

by

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PREFACE

This is the third of a four-part series on Stream Channel Modification (Channelization) in Hawaii and Its Effects on Native Fauna. Part A (FWS/OBS-78/16, Timbol and Maciolek 1968) contains a statewide inventory of perennial streams, channel alterations and aquatic macrofauna. Part B (FWS/OBS-78/17, Norton et al. 1968) contains an intensive year-round study of macrofaunal communities in selected streams and contrasts channelized and natural channels. Part D (FWS/OBS-78/19, Parrish et al. 1978) will contain a general summary of project results. The present report contains a detailed description of environmental conditions in streams that are relevant to the welfare of native species and indicates how channelization affects these parameters. It also reports results of tolerance of native and some exotic species to relevant levels of these parameters. Conclusions regarding the results of channelization for the biota are presented. Data and analysis from January 1977 through October 1978 are included in this report.

This report is part of a thesis submitted to the Graduate Division of the University of Hawaii in partial fulfillment of the requirements for the Master of Science degree in Zoology.

Any suggestions or questions regarding Channel Modification in Hawaii should be directed to:

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EXECUTIVE SUMMARY

Streams in Hawaii have been subjected to water diversion, exotic introductions, and several forms of channelization. The latter have included realignment, clearing of riparian vegetation, and construction of artificial bank and bed structures. Channel modification has been correlated with increases in physicochemical variability and reductions in numbers of several endemic gobiid fishes in altered streams. The amphidromous migratory behavior of the native fauna prevents the isolation of any species from the effects of channelization on water quality.

Daytime values of conductivity, pH and dissolved oxygen were found to be considerably higher in altered streams than in unaltered streams. Temperature was monitored weekly for one year at 20 stations to assess the relative effects of different channel types on thermal fluctuations. All stations located downstream from channel modifications had higher diurnal peak temperatures than upstream and unaltered stream stations. Temperature extremes of 36.2°C and 17.8°C were recorded at the downstream end of a concrete lined channel. Diel changes in temperature of 12°C were not uncommon at this site. High illumination due to clearing of the vegetative canopy, and shallow water depths in lined channels appear to be responsible for the excessive heating.

Tolerances of native species and key exotics to elevated temperatures were determined using a gradual heating method designed to simulate in situ diurnal heating. Growth of post-larval migrating forms of several gobiids was measured following one-month exposures to different fluctuating thermal regimes. Upper lethal temperatures correlated with altitudinal distributions of adult fishes and crustaceans. Lethal limits of those species absent or rare in altered streams fell within the range of temperatures recorded in such degraded habitats. Dominant introduced fishes showed greater resistance to high temperatures than native animals. Maximum growth rates occurred in fluctuating temperatures whose diel maxima were 7-8°C below upper lethal limits.

Where future channel modification cannot be avoided, channelized sections should be kept as short as possible, with natural sections interspersed between them along the length of the stream. Nearstream vegetation should be maintained. Lined channels should contain V-shaped notches at mid-channel or a slanting bottom in order to maximize depth during low flow conditions. Mitigation for existing channels should include revegetation of stream banks.

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LIST OF ABBREVIATIONS AND SYMBOLS IN TEXT

ABBREVIATIONS

cm	centimeters
E.I.F.A.C.	European Inland Fisheries Advisory Commission
hrs.	hours of the day
km	kilometers
km ²	square kilometers
m	meters
min	minutes
NS	not statistically significant
NTU	nephelometric turbidity unit
pH	-log ₁₀ hydrogen ion concentration
ppm	parts per million
PVC	polyvinyl chloride
U.S.E.P.A.	United States Environmental Protection Agency
U.S.G.S.	United States Geological Survey
μmhos	micromhos

SYMBOLS

a	coefficient in length-weight relationship
CO ₂	carbon dioxide
F	statistical test based on F distribution
K	condition factor
LD ₅₀	lethal temperature at time of 50% mortality
N	exponent in length-weight relationship
NH ₄	ammonium ion
NH ₃ ·H ₂ O	ammonia associated with water
P	statistical probability
r	correlation coefficient
r ²	coefficient of determination
SD	standard deviation
t	statistical test based on t distribution
\bar{X}	mean
\bar{X}_d	mean for downstream station
\bar{X}_u	mean for upstream station
○	sampling station
⋮	realigned/cleared stream channel



revetment of stream banks



lined stream channel

°C

degrees, Celsius

°N

degrees, north latitude

°W

degrees, west longitude

%

percent

‰

salinity, parts per thousand

ACKNOWLEDGMENTS

Valuable criticism and willing assistance in laboratory and field work were offered by Susan E. Norton, James D. Parrish and Amadeo S. Timbol. Several collections of organisms were made on Maui and Kauai by John A. Maciolek, whose guidance throughout the investigation was indispensable. James D. Parrish made critical reviews and supervised the preparation of the final copy. Susan Takemoto prepared all figures and illustrations and Dorothy Matsui did the typing.

INTRODUCTION

The high islands of the Hawaiian archipelago stretch from southeast (19°N, 155°W) to northwest (22°N, 160°W) below the Tropic of Cancer. The five islands of Hawaii, Maui, Molokai, Oahu and Kauai make up 96% of the total land area of the island chain and contain the only substantial fresh waters. The 366 perennial or possibly perennial streams represent the dominant freshwater ecosystem (Timbol and Maciolek 1978). Streams tend to be rocky and precipitous, particularly in their upper and middle reaches, with entry into the ocean ranging from waterfalls with rapid mixing to the flood plain situation with river-estuary.

The insular evolution of the indigenous Hawaiian freshwater macrofauna has been influenced by the great distances to the Melanesian faunal source areas (MacArthur and Wilson 1963) and the relative lack of larvae dispersing currents in the vicinity of the islands' mid-gyre position in the North Pacific. The high degree of endemism (78%) among the nine species of native freshwater fishes, shrimps and mollusks illustrates the adaptive radiation to be expected on high islands in such locations.

The five gobioid fish species include Awaous genivittatus, A. stamineus, Sicydium stimpsoni, Lentipes concolor, and Eleotris sandwicensis. All are endemic with the exception of A. genivittatus, which has been reported from Samoa (Jordan and Seale 1906). A sixth endemic species, Kuhlia sandwicensis is a euryhaline opportunist, and as such will not be considered as part of the freshwater fauna.

Two endemic shrimps comprise the native macro-crustacean fauna. Atya bisulcata belongs to the family Atyidae. One of 16 genera, Atya is found in fresh waters throughout the tropical and sub-tropical Indo-Pacific region. Macrobrachium grandimanus is one of the Indo-Pacific circumtropical family Palaemonidae, whose representatives are typically euryhaline.

Two varieties of macro-mollusks are native inhabitants of streams in Hawaii. Neritina granosa, an endemic neritid snail, and several unidentified thiarid snails of the genus Melania, represent the larger Hawaiian aquatic gastropods.

With the exception of Melania spp., the freshwater fauna is "amphidromous", according to the definition of Myers (1949), engaging in life stage dependent, non-gametic migration. This behavior involves the passive downstream passage of eggs or larvae to the ocean during freshet flow with later

active upstream migration. It is particularly adapted to the variable discharge and rugged nature of Hawaiian streams.

In Hawaii and throughout the developed world, the expansion of metropolitan environments has resulted in drastic modifications of freshwater habitats through efforts aimed at increasing flood control capabilities. Two of the first stream alteration projects in Hawaii were initiated in or around 1920, in the interrupted Makiki Stream in Honolulu and Wailoa River in Hilo. At present, over 15% of the State's streams have been subjected to channel modification involving removal of vegetation, realignment, and/or construction of culverts, bank revetments and concrete lined channels. Lined channels are rectangular or V-shaped artificial bank and channel structures. Revetments are reinforced banks without stream bed alteration. These two types of channel modification, along with a third type involving only realignment and removal of vegetative cover, make up 92% of all channelization statewide. Timbol and Maciolek (1978) considered the lined channel to be the most ecologically and numerically significant form of alteration. Although first used in Honolulu's Kapalama Stream in 1938, most in existence today were built within the last two decades. Other activities leading to the further degradation of natural conditions are irrigation dewatering (53% of streams diverted) and the introduction of freshwater exotic species (above data and definitions from Timbol and Maciolek 1978). Brock (1960) reported a 70% success ratio for exotic introductions.

The U.S. Fish and Wildlife Service has supported studies on the impact of channelization in over 20 states. With the exception of water velocity versus fatigue experiments, most of the investigations completed or in progress have dealt with the correlation of physical and chemical parameter measurements with species composition in natural and degraded habitats or examined the effectiveness of mitigation structures in the restoration of game fish (e.g. trout) populations (U.S. Fish and Wildlife Service 1976).

An intensive inventory of Hawaii's streams showed that those containing altered sections had greater means and ranges in temperature, pH and conductivity. The extreme values for these parameters (36.2°C, 10.4 pH units, 368 μ mhos respectively; unpublished data, Hawaii Cooperative Fishery Research Unit) were measured on Oahu where 57% of all perennial streams are channelized (Timbol and Maciolek 1978). The gobiid Sicydium stimpsoni, the mollusk Neritina granosa and the prawn Macrobrachium grandimanus are rare on Oahu, where few if any pristine streams remain. The goby Lentipes concolor may be absent. Miller (1972) has included three Hawaiian endemics in his categories of "threatened" freshwater fishes: Lentipes concolor, "rare" and "endangered" throughout the State; Sicydium stimpsoni, "rare" on Oahu; and Awaous stamineus, "depleted" on Oahu.

Norton et al. (1978) showed that numbers of native animals and total diversity were lower in two altered streams than in an unaltered stream on Oahu. She found no indigenous species in lined channels and hypothesized that the poor water quality and lack of shelter in such locations favored domination by the highly tolerant exotic poeciliid fishes. Timbol and

Maciolek (1978) also reported that no native species were collected in lined channels, suggesting the existence of migration blocks in many streams.

The migratory behavior of the Hawaiian fauna prevents the isolation of any native animal from the effects of channelization on downstream water quality, if not from the necessity of traversing altered sections. Many channelization studies focus on the destruction of physical features known to influence certain key populations, thereby lowering the game fish potential of a stream (e.g. Lewis 1969, Schaplow 1976). The economic and recreational motivation for such works distinguishes them from the situation in Hawaii (in which entire streams become the critical habitats for small populations of organisms of inherent biological value). The present work is an investigation into the role of physicochemical variability induced by stream channel modification in the decline of native animal populations. The emphasis will be given to temperature rather than to those chemical parameters which are measures of complex, often temperature sensitive, ionic interactions not readily simulated in experimental work. This study will examine the dynamics of variation in key water parameters and the effects of elevated temperature on indigenous species.

The literature concerning the effects of temperature on aquatic life is voluminous, with the majority of the work devoted to fishes (e.g. Brett 1956; Doudoroff 1957; Fry 1971). The direct effects of temperature on the physiology and behavior of the individual organism are perhaps less complex than those ways by which temperature may indirectly affect an individual through influences on the entire community. The latter, however, are dependent on the sum total of direct effects on all community members. These effects can be divided among lethal, metabolic and behavioral categories. Fry (1967) uses the corresponding terms "lethal, controlling and directive". Lethal temperatures generally define the range within which the organism will necessarily die in a finite time of causes not related to the metabolic rate. The metabolic and behavioral categories contain what may be considered sub-lethal effects. While the lethal range is one of resistance, the sub-lethal region is that of tolerance. Metabolic effects have been referred to as "delayed action" effects of high temperature (Andrewartha and Birch 1954). An example would be an acceleration of growth resulting in the inability to reach and/or pass a critical point in the life cycle. Behavioral effects include the immediate positive and negative responses to a temperature stimulus and are usually approached with techniques aimed at exploring preference and electivity.

Symons et al. (1976) determined the upper lethal and preferred temperatures of the slimy sculpin in an effort to predict the possible consequences of stream water temperature elevation following clear cutting in the southern part of its range. The present work uses a similar approach in attempting to explain the already apparent results of channelization of streams in Hawaii. Lethal temperatures are determined for native species and the effect of temperature on the post-larval growth of several gobiid fishes is studied. Assuming variability within a population sample's response to lethal and sub-lethal temperatures, data collected may answer some questions concerning the subtle effects of temperature on population

decline despite reproduction (i.e. growth rate constant $r < 0$). However, the effect of environmental variables on population dynamics is beyond the temporal and logistical scope of this and most biometeorological studies.

The existing stream habitat data for Hawaiian streams are sparse and unreliable, particularly in regard to altered streams, where great diel variation necessitates temporal controls on sampling. A goal of this study is the improvement of the significance, if not accuracy, of existing physico-chemical data. Guidelines for future proposed stream modifications must be based on evidence detailing the mechanisms by which the distribution and abundance of Hawaiian stream fauna (Norton et al. 1978) are affected by the results of stream channelization. This investigation should provide the evidence for one of these mechanisms.

METHODS

PHYSICOCHEMICAL SAMPLING

An intensive program of monitoring temperature and other key water parameters was conducted at 20 stream channel stations representing a diversity of channelized and natural habitats (Table 1). Stations were located in the Manoa-Palolo watershed on leeward Oahu and in the Waiahole and Maunawili watersheds on windward Oahu (Fig. 1-4). Two of the Maunawili stations, not shown in Fig. 4 are MW-3, located between MW-1 and MW-4, and MW-5, a sewage outfall adjacent to MW-4. Several of the sites are identical to sites included in a previous study of faunal distribution and abundance (Norton et al. 1978). In most cases, stations were defined more by their relationship to a specific type of upstream or downstream channel than by the morphology of the site itself. This allowed for assessment of the net change in specific parameters following flow through such areas.

Preliminary studies showed that maximum daily water temperatures generally occurred in mid-afternoon, between 1400 and 1500 hours. Weekly measurement of peak diurnal water temperatures by hand held mercury thermometer began in October 1977 at most stations, and ended in September 1978. Addition of stations to the survey after October was prompted by recognition of possible confounding effects due to changes in flow between stations (e.g. sewage outfalls, Station MW-5) and of the need for more precise information from within and between certain neighboring sites.

Measurements of conductivity (YSI Model 33, S-C-T meter), pH (AM Inc. Model 107 Pocket Meter), and dissolved oxygen (YSI Model 57 Oxygen Meter) were included in the latter half of the survey approximately once a month. Water was sampled at depths of 2-10 cm and, where possible at shallow water sites, at the cross-channel position of maximum flow velocity. In order to insure a high degree of statistical authenticity for between-site comparisons, all measurements were made during the same one-hour period, one day each week on windward Oahu and one day on leeward Oahu.

Ranges, means and standard deviations were calculated for all parameters at all stations. A second set of mean temperatures and their standard deviations were determined for each station for comparison with that of the neighboring up- and downstream stations, using only data collected during same-hour, same-day sampling at both stations. Significance of the differences in mean and variance between stations was tested using the "Student's" t statistic, and change in temperature per meter of stream channel

Table 1. Water Quality Sampling Stations

Station	Watershed	Drainage Area (km ²)	Elevation (m)	Width (m)	Distance from Mouth (km)	Channelization ^a	Observation Period
W-1b	Waiahole	10.2	5	3	0.5	none	Oct 77-Sep 78
W-2b	"		67	4	3.9	none	"
MW-1	Maunawili	13.9	21	1	9.4	none	"
MW-2	"		21	2	9.4	none	"
MW-3	"		21	1	9.4	none	"
MW-4	"		23	5	9.5	lined channel	Jan 78-Sep 78
MW-5	Maunawili (sewage outfall)		23		9.5		"
MP-1	Manoa-Palolo	7.0	0	50	0.2	drainage canal	Oct 77-Sep 78
MP-2	"		0	20	2.3	realignment	"
MP-3	"		5	7	3.6	revetment	"
M-4b	"		6	3	3.7	revetment	"
M-5	"		44	3	6.2	lined channel	"
M-6b	"		49	5	6.7	revetment, cleared	Jan 78-Sep 78
M-7	"		50	6	6.7	none	Oct 77-Sep 78

Continued

Table 1 (Concluded)

Station	Watershed	Drainage Area (km ²)	Elevation (m)	Width (m)	Distance from Mouth (km)	Channelization ^a	Observation Period
M-8	Manoa-Palolo		85	2	8.9	none	Feb 78-Sep 78
M-9 ^b	"		104	1	9.3	none	"
P-4 ^b	"		6	5	3.7	lined channel	Oct 77-Sep 78
P-5	"		31	5	4.8	lined channel	"
P-6	"	7.0	82	2	7.2	none	Jan 78-Sep 78
P-7	"		104	2	7.7	none	Oct 77-Sep 78

^aAny major alteration to stream bed, channel or banks immediately upstream from station

^bCorresponds with station in Norton et al. (1978)

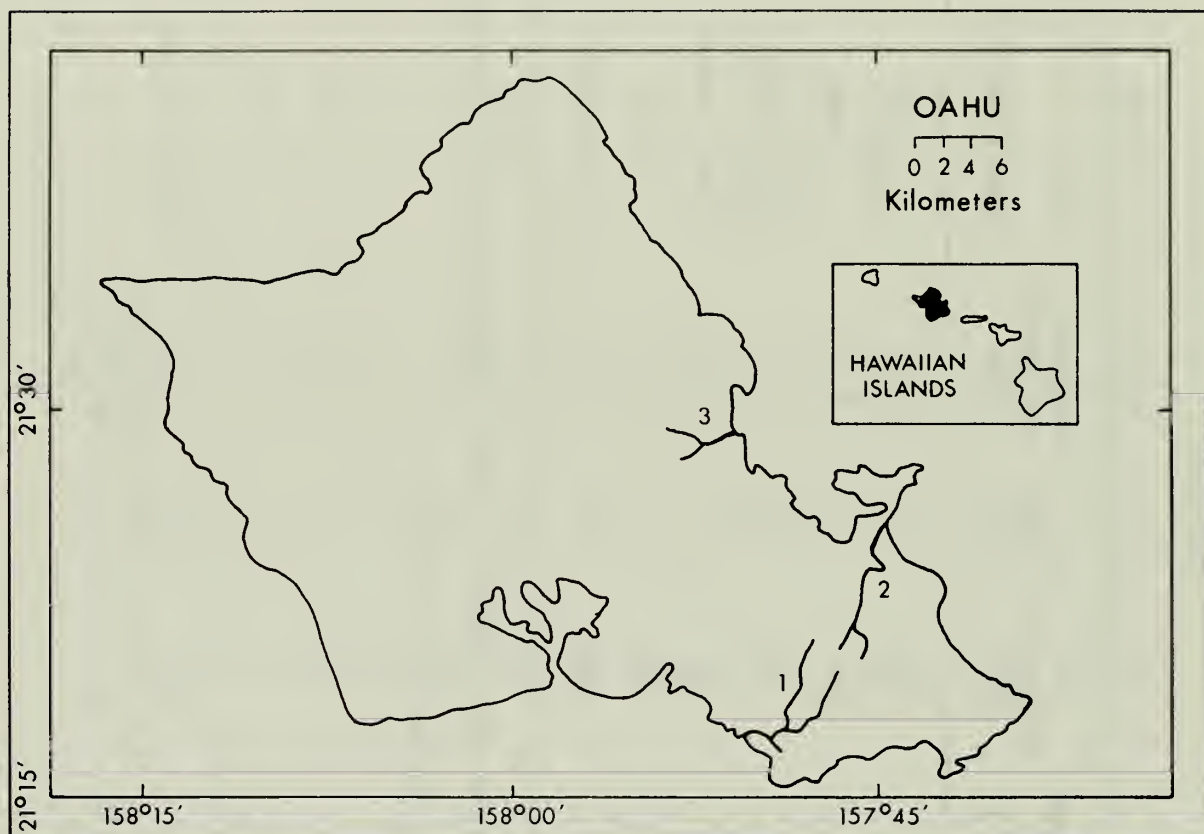


Figure 1. Locations of study streams on Island of Oahu: Manoa-Palolo (1), Maunawili (2), and Waiahole (3).

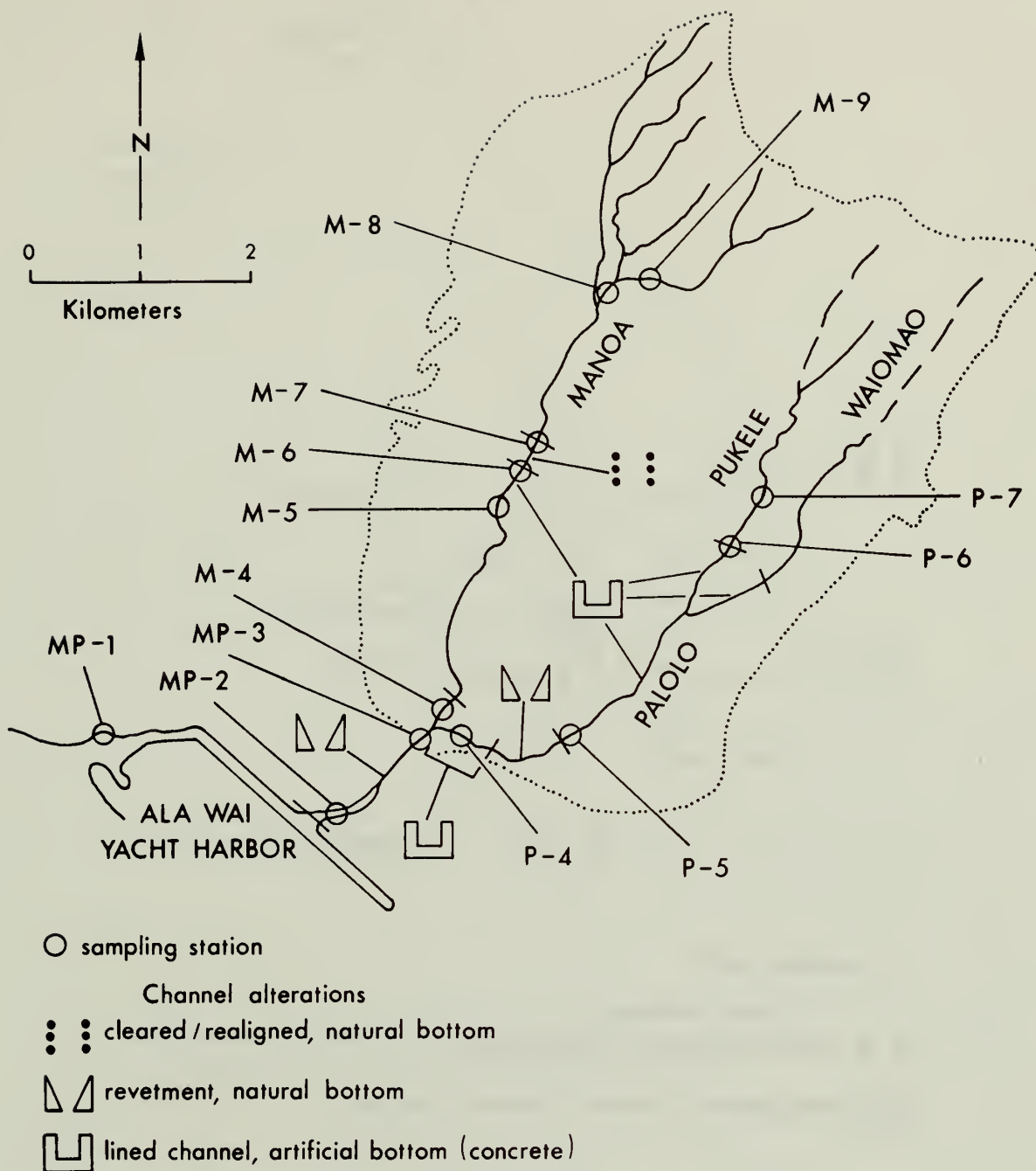


Figure 2. Drainage of Manoa and Palolo Streams, Oahu, showing locations of sampling stations, channelized sections of stream, and watershed limits.

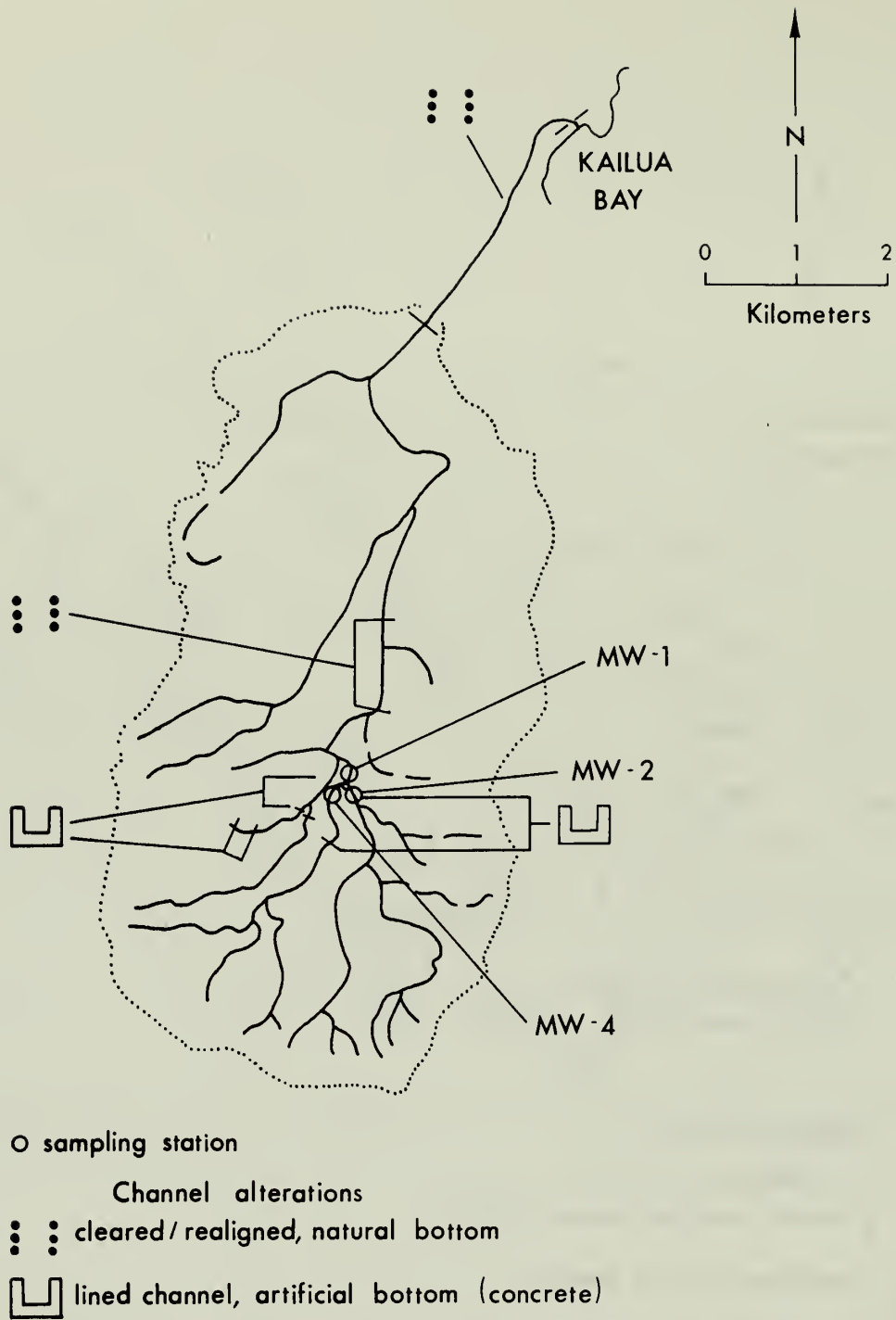


Figure 3. Drainage of Maunawili Stream, Oahu, showing locations of sampling stations, channelized sections of stream, and watershed limits.

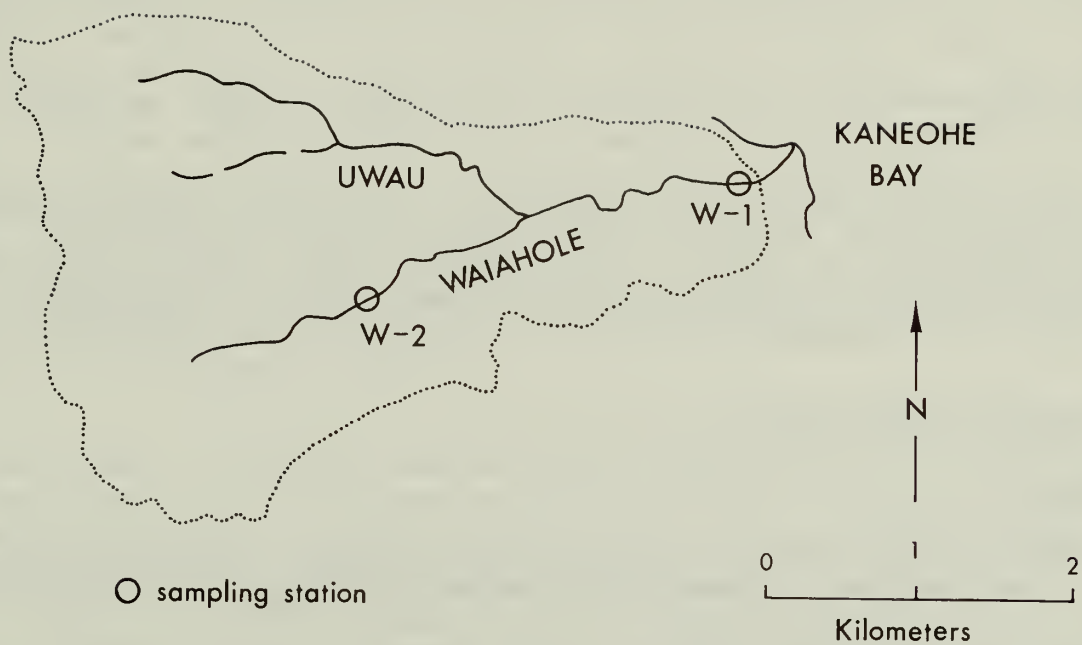


Figure 4. Drainage of Waiahole Stream, Oahu, showing locations of sampling stations and watershed limits.

was calculated. Monthly temperature means for all stations were examined for significant seasonal variation using a one-way analysis of variance.

Stations P-7 and P-5, representing the upstream natural and downstream lined channel conditions respectively, were sampled daily (1400-1500) for one week in April 1978 to examine fluctuations in temperature, pH and conductivity over a six-day period. Twenty-four hour variation in temperature, pH, conductivity and dissolved oxygen at the same two stations was recorded by hourly measurements on one day in September 1978. Diel variation in temperature and pH was recorded at Station P-4 in July 1977.

Illumination (lux) was measured in the shade and in the open (direct unshaded line to sun or region of maximum brightness) at three stations on windward Oahu (W-1, W-2, MW-4) and three stations on leeward Oahu (M-4, P-5 and P-7). All measurements were made with a LI-COR Model Li-185A Photometer, 0.5-1.0 m above the water surface. The probe was oriented upwards at several angles until a maximum reading was obtained, and this value was recorded. Measurements were made between 0800 and 0900, 1100 and 1200, and 1400 and 1500, in February and in late July or early August of 1978.

Water samples were taken for measurement of turbidity (NTU) for several weeks at the regular weekly monitoring time (1400-1500) in August 1978. Only non-freshet flow conditions were sampled, however several stations were sampled during periods of high flow in September 1978 for comparative purposes. Measurements were made using a Hach Model 2100A Turbidimeter.

LABORATORY INVESTIGATIONS

Specimens

Native animals were collected in various streams on the islands of Oahu, Kauai and Maui. Fishes and crustaceans were taken by pole net, dip net, or with a Coffelt Electronics Electro-Shocker Model BP-2 or BP-3. Mollusks were collected by hand. Unless otherwise stated, specimens brought to the laboratory were introduced immediately into 60-liter aquaria with under-gravel aeration and activated charcoal filters. Lava rocks similar to those found in natural stream beds were placed on top of gravel to provide shelter. Lengths of PVC plastic piping (8-12 cm long, 4-5 cm inside diameter) were occasionally used to supplement rock shelter, particularly in tanks containing the prawn M. grandimanus. Aquaria were filled with tap water (pH 7.8-8.2, conductivity 250-280 μ mhos). Aquaria water temperatures showed a diurnal range of approximately 21-24°C, which compares well with the natural variation in middle and lower reaches of unaltered streams. All aquaria received prophylactic treatments through addition of 1-3 drops of a commercial copper sulfate solution prior to introduction of animals. Henceforth, the above conditions shall be referred to as "standard laboratory conditions."

Upper Lethal Temperature Determination

The upper lethal temperatures were determined for all adult and many post-larval/juvenile sub-groups of all indigenous species. Specimens were acclimated to standard laboratory conditions for three days prior to testing. This time period is considered adequate primarily because of the similarity in temperatures of stream collection sites and laboratory aquaria.

Following acclimation, temperature was raised in the original tanks with two 100 watt heaters at a rate of approximately 0.03°C/min until all animals were dead. "Death" was taken to be cessation of opercular movement in fishes, end of physical movements in general in crustaceans, and loss of hold on substrate and/or end of movements in mollusks. The latter is of more ecological importance than it is an indicator of physiological death. For the fishes and crustaceans, the "death" points fall somewhere between the critical thermal maxima (Cowles and Bogert 1944) and true physiological death.

Throughout the study, emphasis was placed on maximum daily temperatures (1400-1500) and the nature of the rate of temperature elevation. In lethal testing, heating was timed so as to simulate natural daily increases in stream temperature, with final temperatures coming in middle to late afternoon. Laboratory mortalities thus compare with those occurring *in situ* when an organism encounters a diurnal temperature elevation to levels outside its zone of tolerance. When the final temperature was above 37-38°C, heating rate fell to approximately 0.01°C/min, however such decreases in heating rate are also observed in the field.

The time and temperature of death for each individual was recorded, and the interval of time and temperature for 100% mortality, as well as LD₅₀, was determined. All animals were measured, and if possible sexed, in order to examine variations in resistance due to size or sex. Fishes were also weighed, and condition factors ($K = (\text{Weight}/\text{Length}^3) \times 10^5$; Carlander 1969) were calculated for comparisons between species and populations.

There are certainly numerous ecological instances when constant temperature lethal testing is called for, particularly in situations of constant thermal effluent from power plants (e.g. Thermal Ecology Program publications, Savannah River Ecology Laboratory, Univ. of Georgia). In the present study, the use of constant temperature techniques appears inappropriate on both ecological and practical grounds: 1) elevated temperatures in streams are not a result of a point source derived effluent, but rather an extension of natural ranges in diel variation; 2) migratory animals are presumably exposed to rapid changes in temperature regime without lengthy acclimation; and 3) availability of most species restricts the testing design.

A major problem in methods of upper lethal determination employing gradual heating concerns the continued elevation of temperature beyond that final point from which survival would be possible. To briefly explore this dilemma, only in order to better clarify results of the upper lethal tests,

a short-term test was performed. Following 3-day acclimation to standard laboratory conditions, samples of several species were subjected to temperature elevation to 33°C on each of two consecutive days. Temperature was allowed to fall to ambient levels for approximately 18 hours following the attainment of the 33°C peak, both prior to and following heating on the second day. Mortalities were recorded.

Long Term Metabolic Effects - Growth

A series of experiments was performed to determine the effect of daily temperature elevation on gross growth in post-larval/juvenile samples of Awaous genivittatus. Individuals were collected by pole net in the lower reaches of Honolulu's Nuuanu Stream. Lengths of all fish were measured immediately after capture, and fish were divided into groups of 10 among buckets for transportation to the laboratory. Each group was introduced into a separate aquarium under standard laboratory conditions.

For 1 month following capture, the temperature of each test tank was elevated daily to a set temperature by means of subsurface heaters. Effort was made to simulate natural heating both in rate and approximate time of peak (1400-1500). Water was then allowed to cool naturally until the following morning, at which time heating would again commence. Average temperatures in treatment tanks were above those in streams with identical maximum temperatures primarily because of slower cooling rates in the laboratory situation.

Each series of experiments involved one, two or three test tanks, and one control in which temperature was allowed to rise naturally to about 24°C each day. The daily minimum temperature in all tanks was approximately 21-22°C. A commercial flake food was introduced into all test tanks daily. Fish were presumably fed to satiation as evidenced by only slight accumulations of uneaten food over the gravel throughout the test period.

At the end of the 30-day periods, mortalities were recorded and lengths of all surviving fish were again measured. By means of the formula

$$\text{Weight} = a \cdot \text{Length}^N$$

(Carlander 1969), lengths at capture and at end of the test period were converted to weights (see Appendix A for species specific values for the "a" and "N" constants). Mean percent increase in weight and mean percent change in variance within each temperature group were calculated. These values were plotted against daily maximum temperature during the test period for each series. The curves produced were examined in relation to the model of Gibbons (1976) which relates population success to thermal loading.

Non-destructive identification of post-larval forms of the genus Awaous is difficult. This resulted in the introduction into experimental tanks of some A. stamineus in addition to A. genivittatus. A. stamineus individuals

tended to be the smallest fishes in collection groups, and suspected members of the species were noted. When the same number of A. stamineus were positively identified after the 30-day growth period, this group was analyzed separately from the A. genivittatus.

A final series of experiments sought to examine the growth-temperature relationship in post-larval Lentipes concolor.

Effects of Reduced Streambed Heterogeneity and Water Depth

The absence of shelter and pool-riffle depth variability in the lined channel distinguishes it most from the unaltered channel. A simple test was devised to obtain preliminary data on the possible deleterious consequences of streambed denudation. Two adult Awaous stamineus and two adult Sicydium stimpsoni were obtained from unaltered streams on Kauai. One fish from each pair was placed in one of two 20-liter aquaria, containing a gravel bottom cover, rock shelters and water to a depth of 20 cm. The other two fishes were placed into identical aquaria except that rock shelters were absent and water depth was held at 8 cm, both attempts to simulate the lined channel morphological situation. Temperature fluctuation in all aquaria was that to be expected under standard laboratory conditions. Fishes were fed a commercial flake preparation every two days. Water was changed and feces collected in each tank approximately once a week.

Following a 130-day period, survivors were subjected to upper lethal temperature tests, and the lethal limit and condition factor of each was compared with that of the other conspecific in the pair, as well as with those of conspecifics utilized in previous testing.

RESULTS

PHYSICOCHEMICAL SAMPLING

Ranges, means and standard deviation of temperature, pH, conductivity and dissolved oxygen, measured between 1400 and 1500 over the entire study, for the twenty sampling stations are shown in Tables 2-5. Mean conductivity, pH and dissolved oxygen all tended to increase with downstream flow. Mean temperature and variance about the mean tended to increase significantly ($P < .05$) with downstream flow. Temperature increase per meter of channel length is shown in Table 6 to be greatest in lined channels. There is, however, variability in heating rates between similar channel types.

Figures 5-8 show the 24-hour fluctuation of the four parameters at the upstream natural bottom station P-7 and its downstream lined channel counterpart P-5. Figure 9 presents 24-hour fluctuation of pH and temperature at station P-4. Only temperature showed maximum values in the 1400-1500 period; pH and dissolved oxygen reached maximum values near 1200. Peak conductivity readings occurred at each station around 1200-1300, however, a larger second peak occurred around 2200 at the lined channel station.

Temperature

Two cases are represented in which water flowing from a lined channel joins that from a much less degraded stream branch (Fig. 2, 3). Stations P-4 and MW-4 were situated at the downstream ends of lined channels slightly upstream of the confluence. They showed higher mean peak temperature, pH and dissolved oxygen than the neighboring stations, M-4 and MW-2 respectively, which were upstream of the junction on the opposing branch.

Distinct thermal stratification was observed below the confluence of "warm" Palolo and "cool" Manoa streams. However, temperatures recorded below the junction at MP-3 were found to be little different from those taken at intervals for some 300 m downstream, and can be considered representative of the water mass created at the confluence.

Stations MP-1 and MP-2 were stratified with respect to both salinity and temperature. Sampling near the surface at these sites produced higher temperature and lower conductivity/salinity readings.

Table 2. Temperature Ranges and Means at
1400-1500 hrs. as Measured over the
Entire Study for 20 Sampling Stations

Station.	No. of Observations	Range (°C)	Mean (°C)	SD (°C)
W-1	49	20.9-25.7	23.1	1.3
W-2	48	19.8-21.9	20.9	0.6

MW-1	49	20.5-24.8	22.9	1.1
MW-2	46	19.7-23.8	22.0	1.1
MW-3	48	21.0-27.3	24.3	1.5
MW-4	37	20.6-26.8	23.8	1.4
MW-5	35	24.4-27.0	25.8	0.8

MP-1	38	24.1-29.0	26.4	1.4
MP-2	49	24.7-31.1	28.2	1.5
MP-3	55	20.5-29.7	26.6	1.8

M-4	61	20.2-27.9	25.2	1.7
M-5	50	20.8-27.5	24.7	1.5
M-6	36	20.4-26.4	23.8	1.2
M-7	50	20.2-25.1	23.2	1.1
M-8	33	19.7-22.7	21.6	0.7
M-9	33	19.5-22.1	21.2	0.7

Continued

Table 2 (Concluded)

Station	No. of Observations	Range (°C)	Mean (°C)	SD (°C)
P-4	61	21.3-35.6	29.9	3.2
P-5	54	23.1-36.2	30.0	3.4
P-6	35	20.8-24.6	23.0	0.9
P-7	55	20.0-23.6	22.3	0.7

Table 3. Ranges and Means of pH at 1400-1500 hrs.
for 20 Sampling Stations

Station	No. of Observations	Range	Mean	SD
W-1	7	(6.9-7.2)	7.0	0.1
W-2	7	(6.9-7.4)	7.1	0.2

MW-1	7	(6.8-7.8)	7.4	0.3
MW-2	7	(6.6-7.7)	7.1	0.3
MW-3	7	(7.7-8.1)	8.0	0.1
MW-4	7	(8.0-8.5)	8.3	0.2
MW-5	7	(5.1-7.2)	6.4	0.7

MP-1	3	----	8.0	0
MP-2	6	(7.9-8.6)	8.2	0.3
MP-3	7	(8.4-9.5)	8.9	0.4

M-4	7	(7.4-8.7)	8.1	0.5
M-5	7	(7.4-8.1)	7.8	0.2
M-6	7	(7.1-8.0)	7.5	0.4
M-7	7	(6.9-7.7)	7.2	0.2
M-8	6	(6.6-7.7)	7.1	0.4
M-9	6	(6.7-7.9)	7.3	0.4

Continued

Table 3 (Concluded)

Station	No. of Observations	Range	Mean	SD
P-4	7	(9.3-10.4)	9.9	0.4
P-5	7	(9.0-10.4)	9.8	0.5
P-6	7	(6.9-7.9)	7.4	0.4
P-7	7	(6.5-7.7)	7.2	0.4

Table 4. Conductivity Ranges and Means at 1400-1500 hrs.
for 20 Sampling Stations

Station	No. of Observations	Range (μ mhos)	Mean (μ mhos)	SD (μ mhos)	Mean Salinity ($^{\circ}$ /‰)
W-1	5	(154-165)	159	4	
W-2	5	(122-141)	133	7	

MW-1	5	(175-195)	183	9	
MW-2	5	(178-199)	193	9	
MW-3	5	(160-181)	169	9	
MW-4	5	(150-169)	157	8	
MW-5	5	(260-372)	319	40	

MP-1	1				31
MP-2	5				25
MP-3	5	(143-219)	185	28	

M-4	5	(149-201)	173	19	
M-5	5	(118-167)	153	20	
M-6	5	(115-174)	150	22	
M-7	5	(110-171)	148	24	
M-8	5	(77-116)	107	17	
M-9	5	(70-127)	111	24	

Continued

Table 4 (Concluded)

Station	No. of Observations	Range (μmhos)	Mean (μmhos)	SD (μmhos)	Mean Salinity ($^{\circ}/\text{‰}$)
P-4	6	(187-358)	269	62	
P-5	6	(122-368)	272	85	
P-6	6	(99-220)	195	48	
P-7	6	(90-204)	181	45	

Table 5. Dissolved Oxygen Ranges and Means at
1400-1500 hrs. for 20 Sampling Stations

Station	No. of Observations	Range (ppm)	Mean (ppm)	SD (ppm)	Mean % Saturation	SD (%)
W-1	4	7.9-8.4	8.1	0.2	95	4.6
W-2	4	8.6-9.0	8.8	0.2	99	1.3

MW-1	4	7.8-8.7	8.4	0.4	98	3.8
MW-2	4	7.8-8.8	8.3	0.5	95	3.8
MW-3	4	8.5-9.3	9.1	0.4	107	4.8
MW-4	4	8.9-10.1	9.6	0.5	113	7.1
MW-5	4	7.2-8.1	7.6	0.4	93	5.1

MP-1	0					
MP-2	4	7.8-9.6	8.7	0.7	111	9.0
MP-3	4	9.3-9.8	9.5	0.2	119	3.0

M-4	4	9.1-9.5	9.3	0.2	110	2.6
M-5	4	10.1-10.7	10.4	0.3	124	4.2
M-6	4	9.0-9.2	9.1	0.1	107	1.3
M-7	4	8.7-9.0	8.8	0.2	102	0.8
M-8	4	8.6-9.2	8.9	0.3	100	2.8
M-9	4	8.5-9.3	8.9	0.4	100	4.6

Continued

Table 5 (Concluded)

Station	No. of Observations	Range (ppm)	Mean (ppm)	SD (ppm)	Mean % Saturation	SD (%)
P-4	4	11.4-15.2	13.5	1.8	181	24.8
P-5	4	10.6-13.9	12.0	1.4	160	18.3
P-6	3	8.7-9.0	8.9	0.2	103	0.6
P-7	4	8.8-9.0	8.9	0.1	102	0.5

Table 6. Comparisons of Mean Peak Temperatures Derived from Paired Samples at Neighboring Stations

Stations ^a	No. of Observations	$\bar{X}_d - \bar{X}_u$ ^b (°C)	Channel Type ^c	Distanced ^d (m)	°C/m
W-2, W-1	48	2.1	1	3400	6.2×10^{-4}
M-9, M-8	33	0.5	1	425	1.2×10^{-3}
M-8, M-7	33	1.5	1	2200	6.8×10^{-4}
M-7, M-6	36	0.6	2,3	200	3.0×10^{-3}
M-6, M-5	36	0.9	4	350	2.6×10^{-3}
M-5, M-4	50	---	1,2,3	2500	-----
P-7, P-6	34	0.5	1	450	1.1×10^{-3}
P-6, P-5	34	7.8	4	2400	3.3×10^{-3}
P-5, P-4	48	---	1,2,3,4	900	-----

^aUpstream station listed first.

^bd=downstream station, u=upstream station.

^cAlterations between stations: 1-unaltered, 2-bank revetment, 3-vegetation cleared, 4-lined channel.

^dHorizontal length of channel between neighboring stations.

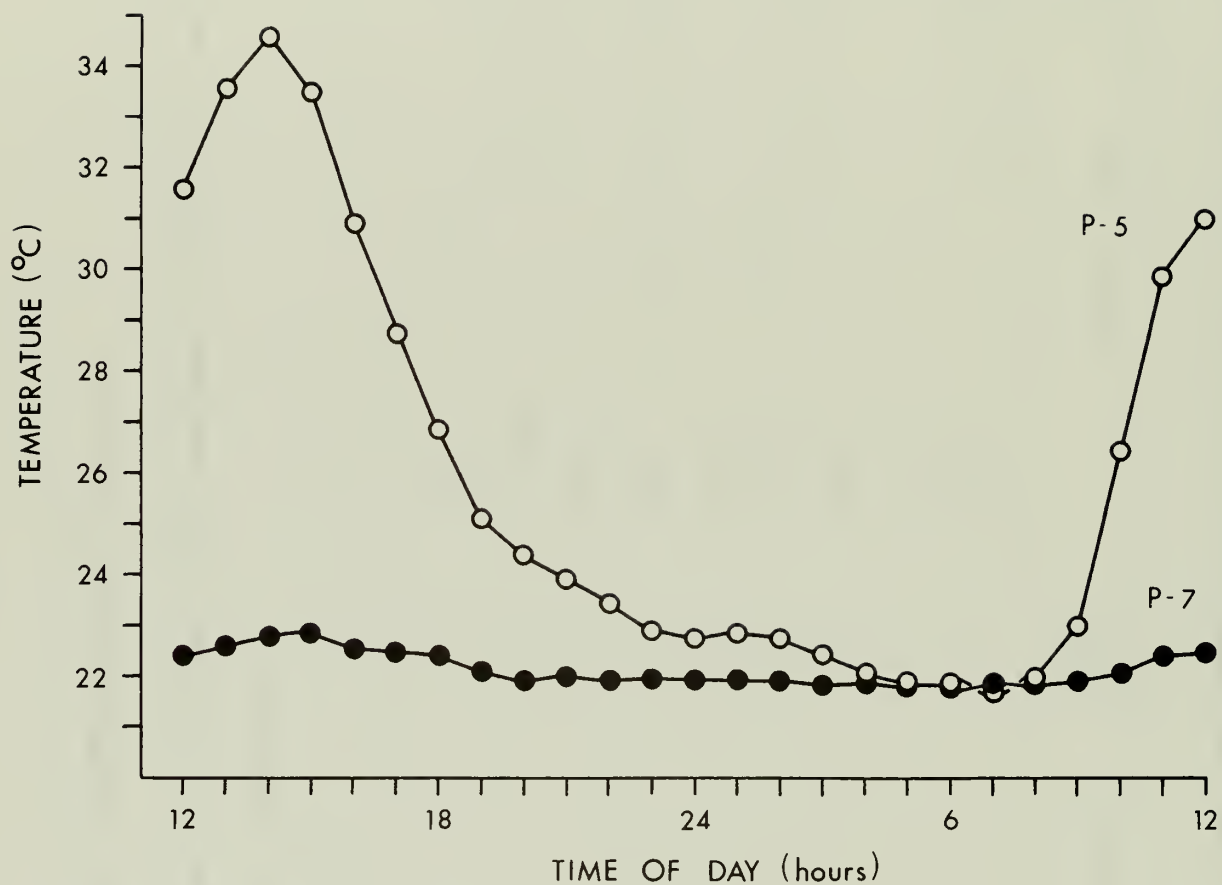


Figure 5. Diel changes in temperature at upstream (unaltered) station P-7 and downstream (lined channel) station P-5 in Palolo Stream, 26-27 September 1978.

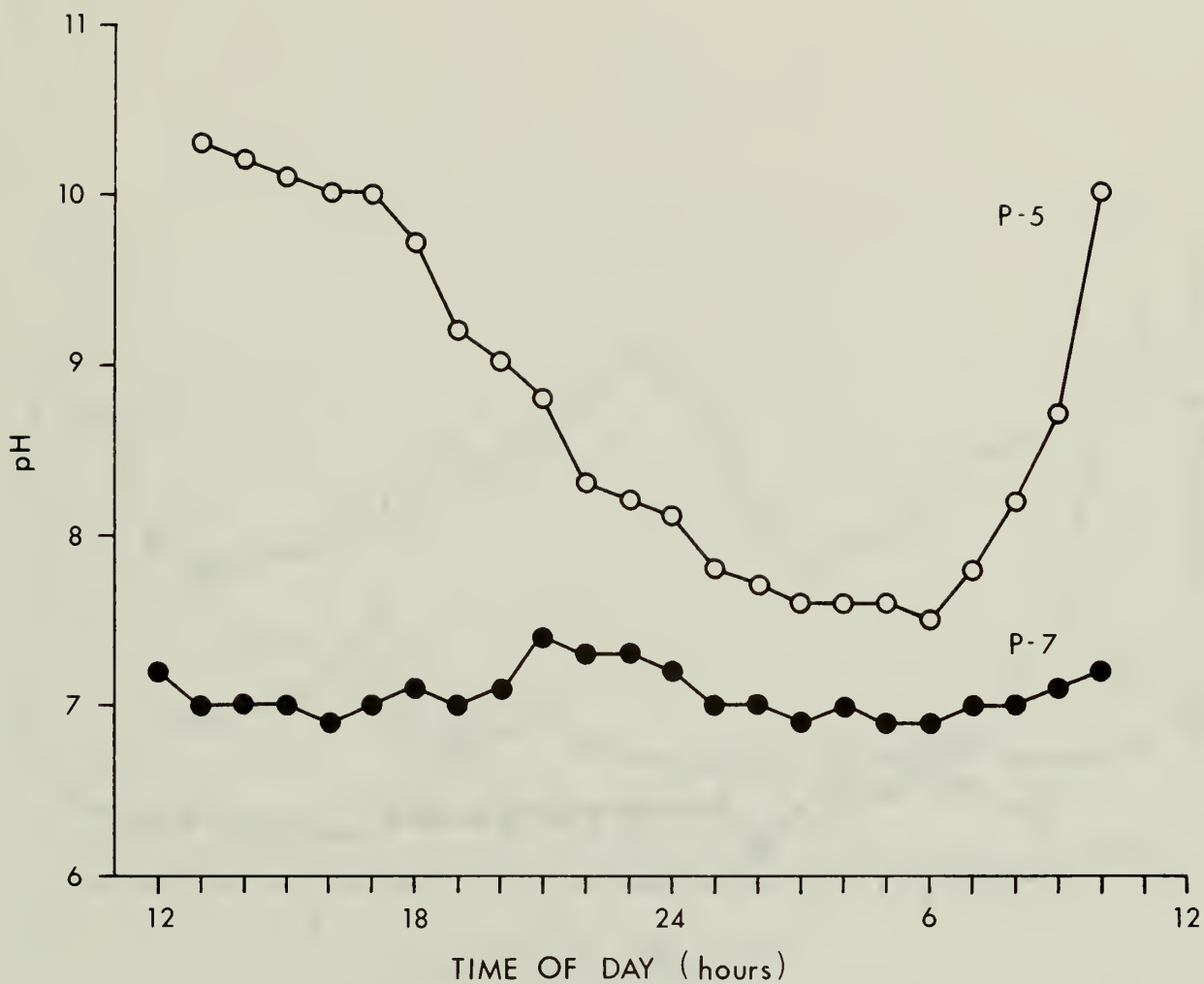


Figure 6. Diel changes in pH at upstream (unaltered) station P-7 and downstream (lined channel) station P-5 in Palolo Stream, 26-27 September 1978.

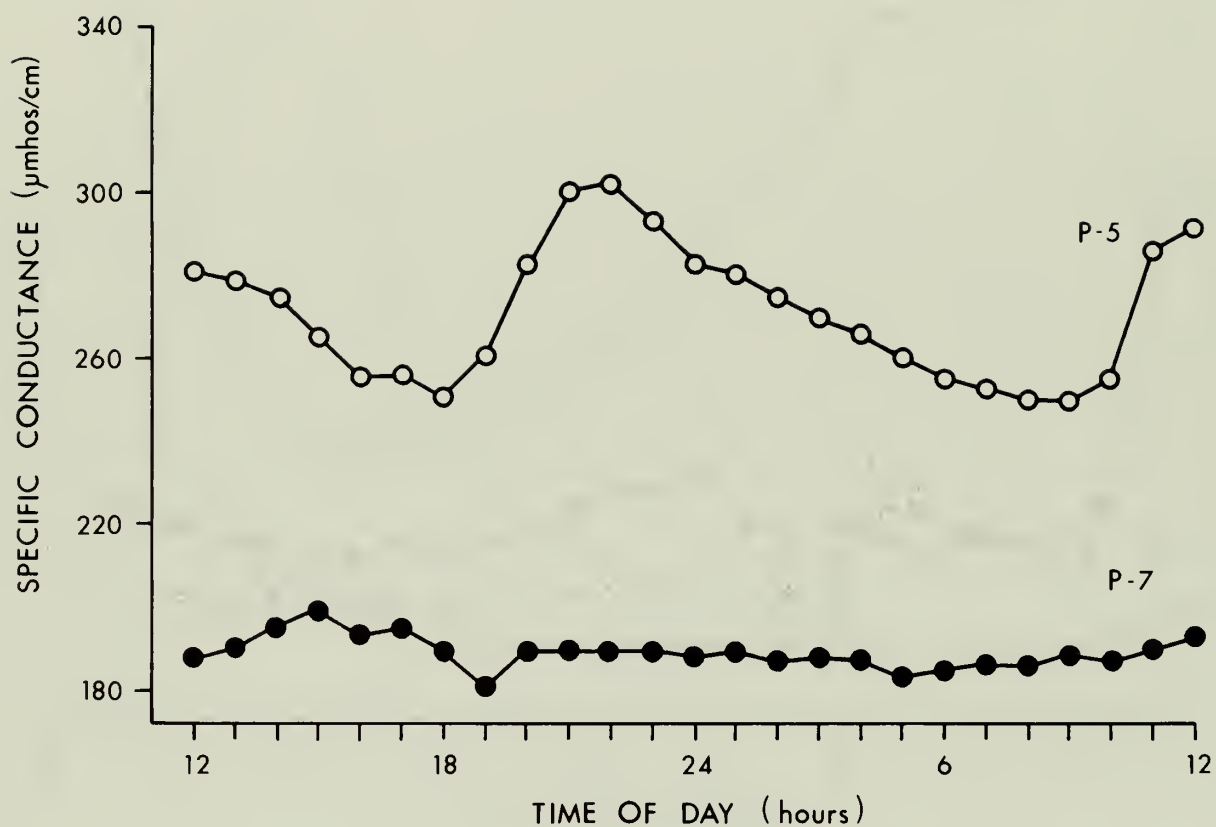


Figure 7. Diel changes in conductivity at upstream (unaltered) station P-7 and downstream (lined channel) station P-5 in Palolo Stream, 26-27 September 1978.

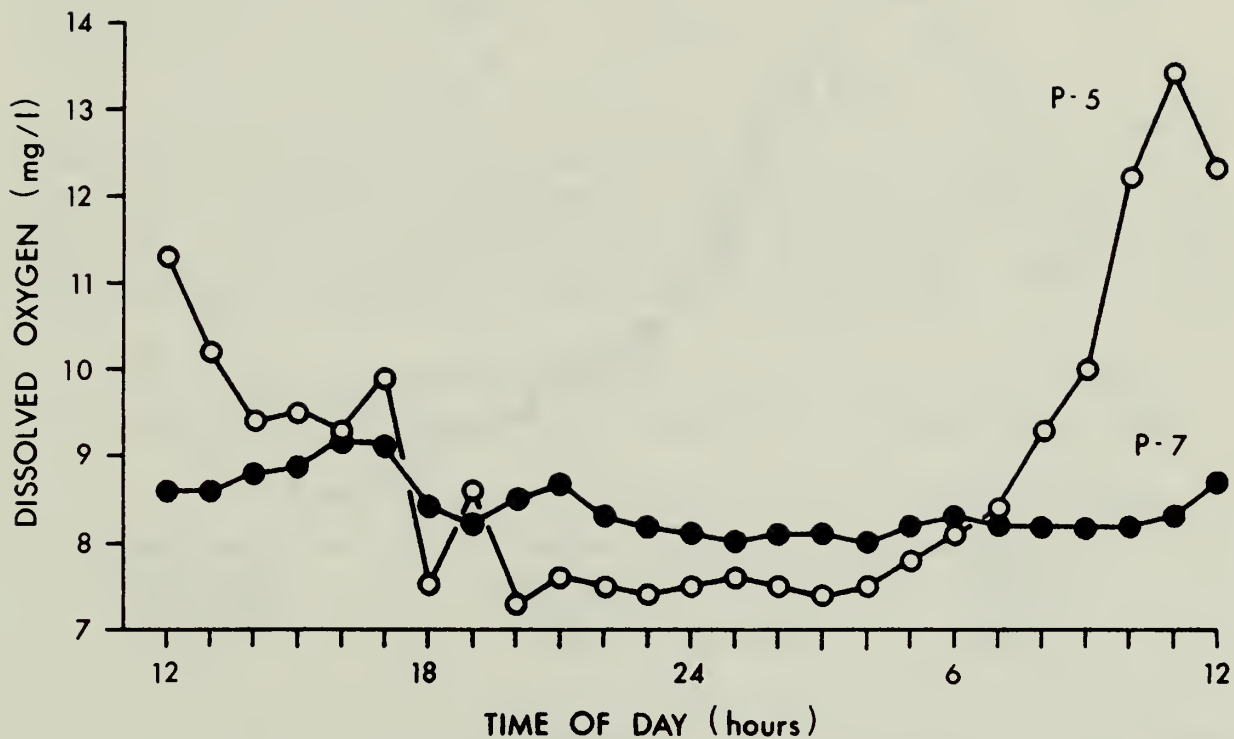


Figure 8. Diel changes in dissolved oxygen at upstream (unaltered) station P-7 and downstream (lined channel) station P-5 in Palolo Stream, 26-27 September 1978.

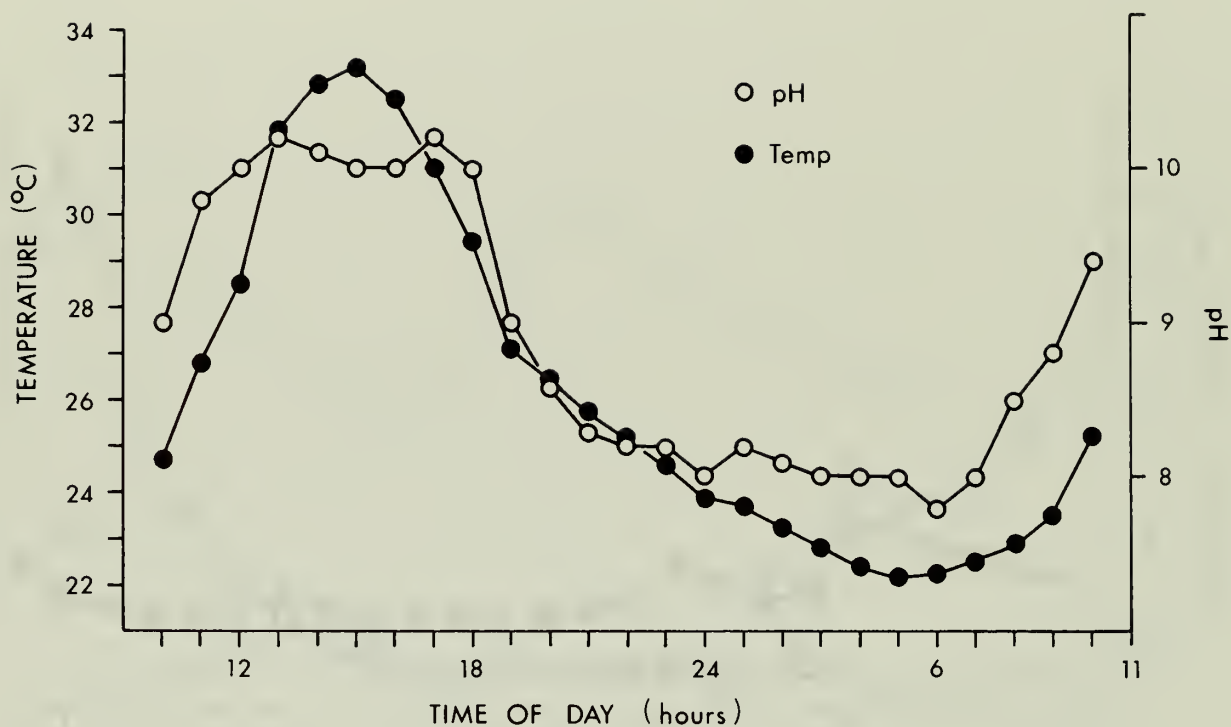


Figure 9. Diel changes in temperature and pH at downstream (lined-channel) station P-4 in Palolo Stream, 21-22 July 1977.

While this study focused on elevated temperatures through examination of daily maxima, minimum temperatures were encountered during work on 24-hour fluctuations and morning illumination measurements. On 10 Feb 78 between 0800 and 0900, the following temperatures were recorded at the stations listed:

P-7	20.8°C
P-5	17.8°C
P-4	19.8°C
M-4	18.8°C

This was the only occasion during the course of the study when temperatures below 19.0°C were recorded in any stream. It was also the only occasion when temperature below a length of lined channel (P-5) was found to be considerably lower than that in the upstream unaltered channel (P-7).

It would be expected that temperature measurement in daylight hours in the region of flow with greatest velocity (typically mid-channel) at most stations would yield the minimum value for the particular station at the particular time (Weekly physicochemical sampling was conducted at mid-channel). It was in fact observed that water in midstream in lined channels had higher velocity and lower temperature than at the edges. Several instances of this phenomenon at station P-5 are shown below:

Time of Day	Temperature at mid-channel (°C)	Temperature at edge (°C)
1400-1500	27.1	31.6
1400-1500	31.9	34.8
1400-1500	36.2	37.2
0730	23.3	23.6

Fluctuations in 1400-1500 temperature, pH and conductivity at stations P-5 and P-7 for six consecutive days in April 1978 are shown in Table 7. It is seen that variances of the measurements about the mean for the six days are comparable to the variances about the annual means for the two stations.

A one-way analysis of variance showed temperature variation between months to account for a significant (F , $P < .05$) proportion of the variation in the annual mean at all stations except P-5 and E-5, which are located at the downstream ends of lined channels. (Stations MP-3, MP-2, and MP-1 were not included in this analysis). All stations had maximum monthly mean temperatures in the period August-October and minimum monthly means in the period December-March. Seasonal progression of monthly mean temperatures was found only at stations M-8, M-7, M-6, P-7, P-6, W-2, W-1, and MW-2.

Table 7. Temperature, pH and Conductivity at 1400-1500 hrs. for Six Consecutive Days

Date	Station P-5			Station P-7		
	Temp. (°C)	pH	Conductivity (µmhos)	Temp. (°C)	pH	Conductivity (µmhos)
9 Apr 78	28.1	9.9	251	22.1	7.1	209
10 "	25.9	8.6	163	20.7	6.8	129
11 "	23.1	8.6	119	20.0	7.0	100
12 "	29.3	9.4	213	21.8	6.6	170
13 "	29.8	9.8	263	22.2	6.6	189
14 "	28.8	9.8	290	22.0	6.6	192
Mean	27.5	9.4	217	21.5	6.8	165
SD	2.5	0.6	65	0.9	0.2	42

These represent all stations located upstream from channelized stream sections with the exception of upstream station M-9, which did not show regular seasonal variation.

Illumination

Only those measurements of illumination made during periods of an exposed sun were considered. This restriction decreased variability in the results but limited the number of possible times for recording.

Maximum values (lux) were measured during noon and afternoon periods. Illumination appeared to be slightly higher in July-August than in February, but values from the different seasons were generally similar.

Maximum illumination values recorded at six stations in both open and shaded conditions are given in Table 8.

Table 8. Representative Maximum Illumination
at Six Sampling Stations

Station	Open (lux)	Shaded (lux)	Channelization
W-2	105,000	530	none
W-1	114,000	3300	none
P-7	114,000	2100	none
MW-4	135,000	6500	lined channel
P-5	147,000	23,400	lined channel
M-4	135,000	12,600	revetment

Mean temperatures from these six stations (Table 2) correlated with the above illumination values from both open ($r=.90$) and shaded ($r=.99$) conditions.

Turbidity

Ranges, means and standard deviations at 1400-1500 of turbidity at the 20 sampling stations are presented in Table 9. All measurements were made at times of moderate flow (i.e. after or during average meteorological conditions). Turbidity tended to increase with downstream flow. This increase appeared to be higher in natural channels than in lined channels, but the trend was not consistent. Representative values for turbidity during freshet flow for several stations are shown in Table 10.

Table 9. Turbidity Ranges and Means at 1400-1500 hrs.
for 20 Sampling Stations

Station	No. of Observations	Range (NTU)	Mean (NTU)	SD
W-1	4	3.4-4.7	4.1	.7
W-2	4	1.1-2.7	1.6	.8

MW-1	4	2.7-12.0	5.7	4.2
MW-2	4	2.5-16.0	6.1	6.6
MW-3	4	2.3-7.7	4.9	2.4
MW-4	4	2.5-7.7	3.9	2.6
MW-5	4	4.5-72.0	22.7	32.9

MP-1	1	----	2.4	--
MP-2	3	2.7-3.0	2.9	.2
MP-3	3	1.6-2.5	2.0	.5

M-4	3	1.7-3.4	2.3	1.0
M-5	3	2.1-2.8	2.5	.4
M-6	3	2.3-2.9	2.6	.3
M-7	3	2.1-3.1	2.5	.5
M-8	3	1.7-3.2	2.6	.8
M-9	3	1.4-2.8	2.2	.7

Continued

Table 9 (Concluded)

Station	No. of Observations	Range (NTU)	Mean (NTU)	SD
P-4	3	1.3-2.2	1.6	.5
P-5	3	1.4-2.5	2.1	.6
P-6	3	1.5-1.7	1.6	.1
P-7	3	1.1-1.2	1.1	.1

Table 10. Representative Turbidity Values for Eight Sampling Stations During Freshet Flow

Station	Turbidity (NTU)
MP-3	11
M-4	13
M-5	41
M-6	37
M-7	25
M-8	31
M-9	12
P-4	4

LABORATORY INVESTIGATIONS

Upper Lethal Temperatures

The upper lethal temperatures for nine indigenous and two exotic species are shown in Table 11. Only in Eleotris sandwichensis trial 1 did acclimation mortality account for a significant portion of the sample. However, the dead individuals were observed to be suffering from leech and parasite infestation at the time of capture. Post-larval samples showed greater tolerance than adults in all cases examined. However, visually observed acute stress appeared at lower temperatures in the former.

There was no relationship between tolerance and size, sex or condition factor. It was hypothesized that any selection caused by degraded environments on upstream migrants would be reflected by a relationship between tolerance and collection site. Trials 1 and 2 for both Awaous stamineus and Eleotris sandwichensis adults utilized organisms from natural (Manoa Stream, Kauai and Waiahole Stream, Oahu respectively) and degraded (Palolo Stream¹ and Moanalua Stream, Oahu respectively) environments. There were

¹A. stamineus was collected between station P-6 and P-7, upstream from the extensive Palolo lined channel. Small numbers were also regularly observed in a mid-channel pool in the funnel of a spillway approximately 200 m upstream from station P-5. Norton et al. (1978) collected no native fishes in this or any other lined channel. Native fishes above the Palolo lined channel have not been reported heretofore.

Table 11. Upper Lethal Temperature Limits of Native and Selected Exotic Species

Species	Sample	Trial No.	Time ^a (min)	Temperature ^a (°C)	LD ₅₀ ^b (°C)
Mollusks					
<u>Neritina granosa</u>	12 adult	1	170	38.4-40.1	38.8
<u>Melania sp.</u>	20 adult	1	89	36.7-38.6	37.5
Crustaceans					
<u>Atya bisulcata</u>	15 adult	1	27	34.0-34.5	34.2
"	25 post-larvae	1	40	34.9-36.1	----
<u>Macrobrachium grandimanus</u>	27 adult	1	35	36.4-36.5	36.5
"	21 adult	2 (33°/‰)	81	36.8-37.3	37.2
Pisces					
<u>Awaous genivittatus</u>	10 adult	1	44	39.2-39.7	----
"	16 adult	2	34	39.4-39.7	39.7
"	10 post-larvae	1	38	39.5-40.1	39.9
<u>Awaous stamineus</u>	5 adult	1	55	37.2-38.7	38.1
"	4 adult	2	45	37.2-38.8	38.4
Continued					

Table 11 (Concluded)

Species	Sample	Trial No.	Time ^a (min)	Temperature ^a (°C)	LD ₅₀ ^b (°C)
<u>Awaous stamineus</u>	25 post-larvae	1	23	39.0-39.3	39.3
<u>Eleotris sandwicensis</u>	1 adult	1	--	39.2	----
"	6 adult	2	30	39.2-39.6	39.3
<u>Sicydium stimpsoni</u>	3 adult	1	7	35.7-35.8	35.8
"	4 adult	2	14	35.4-35.6	35.5
<u>Lentipes concolor</u>	6 adult	1	5	35.9-36.1	36.0
"	9 adult	2 (33°/oo)	15	36.1-36.3	36.2
<u>S. stimpsoni/L. concolor</u>	11 post-larvae	1	23	36.2-36.5	36.4
<u>Poecilia mexicana</u>	12 adult	1	25	41.2-41.4	41.3
<u>Sarotherodon sp.</u>	12 adult	1	17	42.7-43.1	42.9

^aRange for mortality interval (first death to final death).^bTemperature at time of 50% mortality.

no population differences in tolerance within the small samples. Mean condition factor did not vary significantly between populations.

Acclimation to near 100% seawater resulted in increased tolerance to elevated temperatures in both Macrobrachium grandimanus and Lentipes concolor. Euryhaline species typically show greater resistance in saline media. (Remane and Schlieper 1971). Previous investigations showed that neither species of Awaous could survive in salt solutions above 15‰. (Hawaii Cooperative Fishery Research Unit, unpublished data).

Temperature elevation to 33°C on two consecutive days resulted in no mortality in Awaous genivittatus, A. stamineus, Lentipes concolor or Neritina granosa. The shrimp Atya bisulcata suffered 24% mortality in an adult group and 3% in a post-larval group.

In a separate trial without organisms, dissolved oxygen levels were found to decrease from 8.1 ppm at 22.8°C to 6.1 ppm at 38.1°C. Such concentrations should not pose any physiological problems to the organisms. Saturation remained above 90% throughout the test.

Temperature Effects on Growth

The results of four series of tests on the effect of daily temperature elevation on the growth of post-larval gobies are summarized in Table 12 and Figures 10 and 11. In each series, there were no significant differences between initial mean weights among temperature/species groups. With the exception of Series 6C, the month-long tests resulted in significant growth ($P < .01$) in all temperature groups. However, in few cases were differences between final mean weights of series groups significant. Treatment mortalities were insignificant with the exception of total mortality in Series 6C at 35°C.

All series show the trend of growth enhancement with increasing temperature up to a temperature for apparent optimal growth. Percent change in standard deviation within the sample has a similar relationship to temperature. However, while in phase with changes in growth, differences in change in standard deviation between series groups tend to be more pronounced.

Lack of shelter appeared to have little effect on gross growth in Awaous genivittatus. In A. stamineus, the lower growth in tanks without shelter was more pronounced. Increase in variance was less for both species in tanks without shelter. The effect of absence of rock shelters is comparable to the effect of temperature elevations above that for optimal growth.

Differences between series were considerable. Average initial weight in temperature groups was not clearly related to discrepancies in mean growth for identical treatments. Species sample size appeared to account for more of these differences, particularly in the mixed Awaous groups of Series 6B.

Table 12. Summary of Results of Growth vs Temperature Tests

Series	Species	Sample Size	Mortality (No.)	Temp. ^a (°C)	% Mean Increase ^b	% Change SD C
6	<u>Awaous genivittatus</u>	10	0	Cd	202	165
6	"	9	0	30	268	723
6	<u>A. stamineus</u>	1	0	30	125	---

6A	<u>A. genivittatus</u>	11	0	Cd	193	340
6A	"	10	0	28	342	650
6A	"	10	0	32	400	746
6A	"	8	1	34	362	444
6A	<u>A. stamineus</u>	1	0	34	127	---

6B	<u>A. genivittatus</u>	7	0	Cd	300	700
6B	"	6	0	30 w/shelter	658	1700
6B	"	6	1	30 w/o shelter	646	1054
6B	"	8	1	36	555	1317

Continued

Table 12 (Concluded)

Series	Species	Sample Size	Mortality (No.)	Temp. ^a (°C)	% Mean Increase ^b	% Change SD ^c
6B	<u>A. stamineus</u>	3	1	C ^d	146	359
6B	"	4	0	30 w/shelter	884	1630
6B	"	4	0	30 w/o shelter	741	540
6B	"	2	0	36	224	-536

6C	<u>Lentipes concolor</u>	6	0	C ^d	9	-17
6C	"	5	0	30	0	9
6C	"	6	6	35	---	---

^aDaily maximum temperature during month test period.^bIncrease in weight as calculated from species specific weight vs length formulas.^cChange in standard deviation about the mean weights.^dC=Control test tanks; daily maximum temperature=24°C.

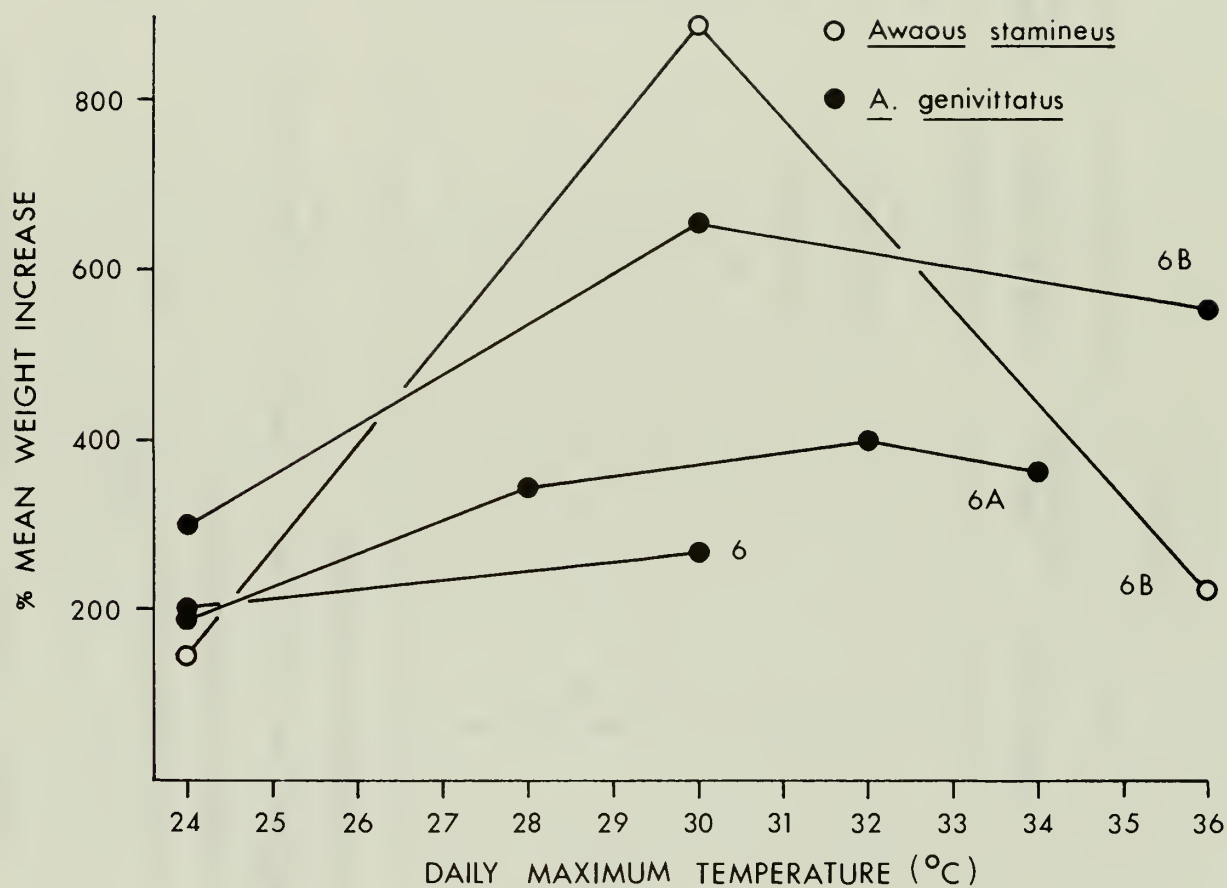


Figure 10. Growth of Awaous genivittatus (Series 6, 6A and 6B) and A. stamineus (Series 6B) during one month of exposure to different fluctuating temperature regimes.

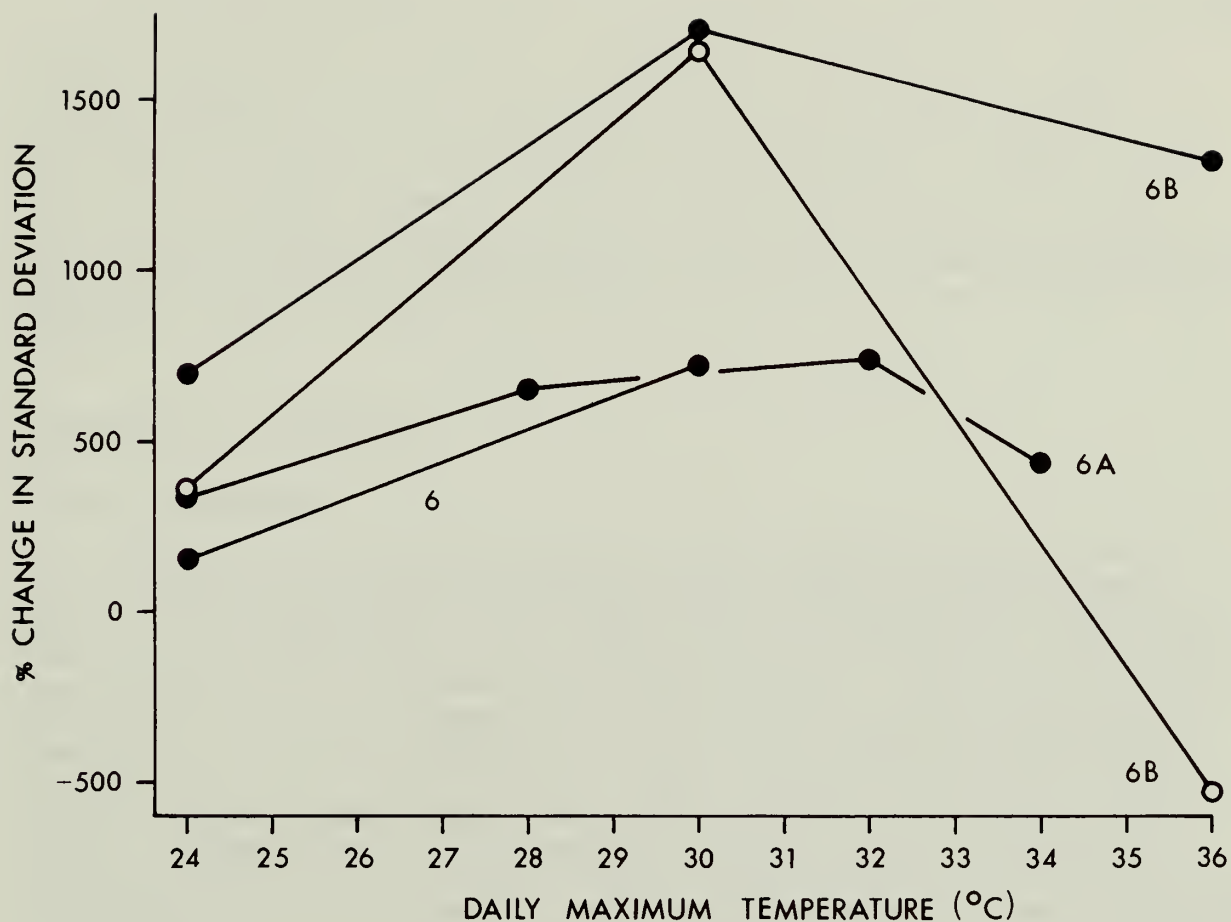


Figure 11. Percent change in standard deviation of mean growth in Awaous genivittatus (Series 6, 6A and 6B; closed circles) and A. stamineus (Series 6B; open circles) in different fluctuating temperature regimes.

Effects of Reduced Streambed Heterogeneity and Water Depth

No mortalities among the four test fishes occurred over the 130-day period. Upper lethal temperatures did not differ significantly between treatments and were within the range for mortality of conspecifics previously tested (Table 11). The results of this test were generally inconclusive.

DISCUSSION

Stream channelization attempts to accomodate and counter the deleterious effects of high flow in areas of variable rainfall and run-off. In populated areas of Hawaii housing is dense, close-spaced, and often very close to streams. Removal of ground cover and impervious land use have made stream bank and bed modification the accepted first defense against flooding. However, such alterations have recently been correlated to changes in the biological and physicochemical characteristics of entire streams (Norton et al. 1978; Timbol and Maciolek 1978). The present study has focused on the tolerance of native stream organisms to the kind of elevated temperatures that must necessarily be encountered by specific life stages in channelized streams.

ENVIRONMENTAL VARIABILITY

Chemical Parameters

The elevation of chemical parameters (pH, dissolved oxygen, conductivity) is clearly related to the presence of channelized stream sections, particularly lined channels. The increases in pH and dissolved oxygen with flow in altered Manoa and Palolo streams contrast with decreases over the same distances in the unchannelized Waiahole Stream. Diel variations in pH and dissolved oxygen were generally in phase, and mid-afternoon maxima in downstream lined channel stations (P-5, P-4) greatly exceeded those above the alteration (P-7) (Fig. 6, 8, 9). Algal photosynthetic activity in highly insolated stream sections may account for these elevations (EIFAC 1969). An examination of U.S. Geological Survey water data for Palolo Stream for 1975-76 (U.S.G.S. 1977) revealed that for the two days on which their sampling was conducted, the only significant chemical changes resulting from downstream flow from the vicinity of station P-7 to P-5 were increased dissolved iron, increased pH, increased conductivity and decreased free CO₂. Dissolved oxygen was not included in their measurements.

Only within downstream lined channel stations P-4 and P-5 in Palolo Stream did mean pH exceed values generally considered suitable for mixed aquatic fauna (Ellis 1937; Doudoroff 1957; State of Hawaii 1978; U.S.E.P.A. 1976). Mean mid-afternoon pH and temperature for stations P-4 and P-5 in lined channels would, in addition, maintain a potentially hazardous level (72%) of toxic unionized ammonia ($[\text{NH}_3 \cdot \text{H}_2\text{O}]/[\text{NH}_3 + \text{NH}_4]$; U.S.E.P.A. 1976).

Conductivity increase during flow through lined channels exceeds that in natural channels. However, tributary (MW-2 vs MW-4) and watershed (Manoa vs Palolo) differences and the unexplained bimodal diel fluctuations (station P-5) discourage more precise statement of the relationship to channelization. Stations P-4 and P-5 have not infrequently yielded conductivity values in excess of the 300 μ mhos maximum criterion for Hawaiian stream water quality (State of Hawaii 1978). However, the generally high tolerance of salinity by the diadromous native fauna suggests that such levels would not be critical (Hawaii Cooperative Fishery Research Unit, unpublished data).

Turbidity

Turbidity values reported in this study compare well with values recorded in similar channel types under similar flow conditions (U.S.G.S 1977). The lack of exposed sediment within lined channels and the urbanization of leeward Oahu account for the lower stream turbidity in the Manoa-Palolo system as compared to that of the Maunawili and Waiahole drainages. Higher variation in turbidity in windward Oahu streams may result from higher rainfall in that area. The principal problem associated with high turbidity in lotic waters is the disappearance of spawning habitat where suspended loads finally settle. The nature of amphidromous behavior coupled with the short incubation periods for the gobioid eggs (Ego 1956; Tomihama 1972) make this less of a problem. Only during the alteration construction itself should turbidity become a potential concern.

Temperature

Mean diurnal peak temperatures for stations W-1, W-2, M-4, M-6, M-9, and P-4 were higher than mean temperatures for the same sites as reported by Norton et al. (1978). This is explained by the rigid temporal control on sampling in the present study which ensured measurement of maximum daily values.

Mean peak temperatures at stations located downstream from some form of channel alteration (Tables 1,2) exceeded that of the downstream station W-1, in the unaltered Waiahole Stream. With the exception of stations MW-4 and M-6, such stations below channelization thus exceeded published criteria for Hawaiian stream water quality, namely, a departure of 1°C from "natural conditions" (State of Hawaii 1978). The high variance about the mean peak temperatures at stations below channelized sections may result in as great a stress as the elevated average. Lined channel station P-5 showed higher variance than the "natural" upstream station P-7 in both daily and hourly temperature fluctuations.

The average diel variation in temperature at stations P-4 and P-5 exceeded the annual variation in many unaltered streams (e.g. Waiahole). That extreme forms of channelization may also result in excessive cooling as well as heating is suggested by the single measurement of morning temperatures in lined channels well below those upstream and above the alteration. Such occurrences are considered infrequent. On the occasion of the observation, unusually low air temperatures and high wind velocity

persisted throughout the night prior to the sampling. However, it is not surprising that a channel without cover should exaggerate heat exchange in both directions. There are observations that shaded temperate region streams are the coolest streams in summer and the warmest in winter (Edington 1965).

The increase in temperature per meter of channel length during mid-afternoon downstream flow is a function of the temperature of the water entering a particular type of channel as well as the type of channel itself. The potential for heating "cool" upstream water during passage through exposed channels is best illustrated by the changes in water temperature between stations P-6 and P-5. With the exception of P-5, all freshwater stations had minimum 1400-1500 temperatures around 20-21°C. The effect of the long lined channel on water temperature is maintained despite high flow and adverse meteorological conditions which tend to buffer physicochemical changes with downstream flow through most channel types.

The 2400 meters of uninterrupted lined channel between P-6 and P-5 was shown to result in an average temperature increase of 7.8°C during mid-afternoon. The temperature elevation per meter of channel averaged over this 2400 meters was the highest determined in this study. However, sampling during the 1400-1500 period at several locations between P-6 and P-5 revealed that heating between the two stations was not always a linear process. Large temperature increases and significant decreases were found to occur over relatively short lengths of channel. Temperatures slightly higher than those recorded at station P-5 were measured during the same time period at a location approximately mid-way between P-6 and P-5.

Increased convective heat transfer from water to ambient as water temperature increases, coupled with rapid cooling of heated water during flow through shaded areas, could explain this non-linearity. This general capacity for sustained though diminishing temperature elevation is of great biological importance. Becker (1975) showed that a rise of 1.0°C often separated zero and total mortality. The results of the upper lethal tests in this study support this result. Thus, while short sections of exposed lined channel can result in rapid water heating, longer sections can be responsible for continued slower heating, and cooling of heated water is a function of the degree of shade cover and the length of channel through such cover.

In the two cases where no significant difference was found between mean peak temperatures from neighboring stations, the upstream station was located at the downstream end of a lined channel. Water at such a point is likely to increase in temperature with further flow only if the channel immediately downstream is also concrete lined. This was not the case in either instance.

The large increase in temperature between stations M-9 and M-8 within an unaltered stream region may be due to run-off of heated surface water used in nearby small scale horticulture operations. It may also be the result of a slight decrease in shade cover or increased exposure to

afternoon sun following emergence from behind a steep ridge. The tributary adding water to the flow from station M-9 just upstream from M-8 is not a source of warmer water.

The slightly higher rate of heating in the revetted/cleared section between stations M-7 and M-6 as compared to that within the lined channel immediately downstream may be another example of higher longitudinal heating rate at lower water temperature. However, the lined channel between stations M-6 and M-5 has an unusual amount of shade cover over part of its length. The shallow depth of flow throughout may have resulted in the continued heating to station M-5. This sheet-like flow over the smooth concrete bottom of the lined channel and the high heat transfer by concrete would appear to augment the basic effects of increased insolation.

Illumination

The high rates of heating occurring in revetted, cleared and lined channels suggest that a combination of intense insolation and reduced cover accounts for most of the temperature increase. Numerous studies have documented increases in downstream maximum temperatures following riparian woodland clearing in upstream areas (e.g. Brown and Krygier 1970; Gray and Edington 1969). In the present study, mean temperatures at six stations showed high correlation with illumination.

The illumination data generally reflect the amount of nearstream vegetation available at the site. A small clearing in a high elevation, natural channel (W-2, P-7) will receive less illumination due to blocking of light from portions of the cosine detection arc of the probe. More extensive clearing and absence of tall vegetation in altered and downstream areas increases the amount of light reaching the stream. Differences between similar stations from windward and leeward Oahu may be due in part to the shade provided by steep mountain ridges on the windward side. Only in topographically flat areas of the same latitude will temporal light patterns be the same (Horn 1971).

It is apparent from Table 8 that the major difference between stations (i.e. channel types) lies in the illumination beneath shade rather than that in the open. The low light levels beneath shade at lined channel station MW-4 compared to those at lined channel station P-5 reflect the maintenance of the natural overhead cover. The 60° angle of the concrete walls of the Maunawili lined channel, as compared to the vertical walls of the Palolo lined channel, may be the result of construction which does not require heavy removal of nearstream vegetation.

Where riparian cover removal has been nearly equal, as at stations P-5 and M-4, water in the lined channel receives more illumination than in the revetment type channel. This is likely due to the reflection of sunlight from the vertical concrete walls. (Revetted walls are seldom vertical and usually have broken surfaces of rock and masonry). This focusing effect of the rectangular lined channel may be important to diurnal heating.

Nocturnal cooling by back radiation would theoretically be facilitated more by the more open, sloped wall lined channel.

Seasonal Variation

Hawaii is generally considered to have two annual seasons. While short-term stream temperature variation at all stations in this study appeared comparable to the annual variation, natural channel stream sections generally adhered to the cool, wet winter vs. warm, dry summer climatic picture. Channelization appeared to obscure the effects of seasonal variation on stream temperatures. This is the result of increased daily and weekly variability, suggesting that alteration makes a stream section more vulnerable to the vagaries of local weather conditions. It is unlikely that this confusion of seasonal cycles would pose major problems to stream inhabitants. In view of the low level of annual variation in the natural stream channel it seems unlikely that animals have developed a reliance on critical temperatures for migration, spawning or egg hatching such as exists in temperate communities.

TEMPERATURE TOLERANCE

Upper Lethal Temperatures

Upper lethal limits determined in this study represent the maximum stream temperatures for species survival. This assumes exposure to the continuum of sub-lethal temperatures during elevation and thermal acclimation comparable to that of the individuals tested. Temperature elevation to slightly lower temperatures would in practice cause total mortality because of the lethal effects of prolonged exposure to sub-lethal temperatures during cooling. It was shown that Atya bisulcata was the only species to suffer mortality during or following temperature elevation to 33°C on two consecutive days. A. bisulcata also had the lowest upper lethal limit of any species tested. This relationship between the lethal limits determined and the effect of heating to and cooling from a slightly lower sub-lethal temperature is shown in growth series 6C. Lentipes concolor suffered total mortality following temperature elevation to 35°C. Its previously determined lethal limit was 36.0°C.

Temperatures were measured in the Palolo lined channel which exceeded the lethal limits of Atya bisulcata, Lentipes concolor and Sicydium stimpsoni. There are no known records of these species from the middle or upper reaches of Palolo Stream. However, A. bisulcata is present in Manoa Stream today, and there are records of S. stimpsoni from "Manoa Valley" (C.H. Edmondson, 1928: Bernice P. Bishop Museum specimen #4841). There is little reason to believe that the two species did not once inhabit "Palolo Valley". L. concolor was reported from Oahu by Gunther (1880). The collection site was listed as "Honolulu", however this does not necessarily indicate presence within what are now the boundaries of the city proper. Nevertheless, the elimination of A. bisulcata and S. stimpsoni from Palolo Stream as a result of acute thermal stress remains an intriguing possibility.

Lined channel "edge" temperatures are likely more significant to the ecology of the post-larval upstream migrant than are those from mid-channel. During most discharge conditions, water velocities at mid-channel would likely prevent stream ascent or at least create an energetically unfeasible situation. Temperatures exceeding the lethal limit of Macrobrachium grandimanus (and therefore those of the three species mentioned previously) were recorded at channel edge in the Palolo lined channel.

Crustaceans showed lower thermal tolerance than sympatric fishes. Fish and crustacean lethal limits were lower for species whose adult habitat is at higher elevations, with the exception of L. concolor which showed greater tolerance than its downstream neighbor, S. stimpsoni. Mizuoka (1962) found the same relationship between tolerance and stream elevation in studies on two Japanese gobiids. He also showed that population differences in tolerance for the lower stream species were related to altitudinal distribution. In this study, the trend was not observed in the two species of mollusks. The ecological death point indicated higher tolerance in Neritina granosa, which inhabits riffles and necessarily maintains a stronger hold on substrate than do the Melania species.

The role of the lined channel in excessive nocturnal cooling of stream water during downstream flow was not formally addressed in this study. The data collected suggest that such cooling is uncommon in comparison to the heating which occurs most regularly. However, Fry (1960) points out that acclimation response is more rapid at high temperatures than at low temperatures, and consequently, in fluctuating temperatures a fish becomes more resistant to high temperatures and more sensitive to the low temperatures. A single occurrence of an extreme temperature drop in the lined channel could be a lethal event if organisms became exposed to conditions below their upward adjusted tolerance ranges.

Numerous studies have shown that fishes will move to cooler waters when subjected to the stress of high temperatures (e.g. Graham 1974). Such behavioral modification is most common in the vicinity of point source effluent outfall. The situation in Hawaiian streams does not allow for horizontal or vertical evasion of the heated water. The existence of the lined channel along a migratory route poses two similar problems. Downstream migrants or wanderers would experience a rapid rise in temperature upon entering a lined channel at mid-day or a slow rise when entering during a cooler period. Fishes which cannot partially acclimate during temperature elevation would experience less stress if the rise were rapid (Jacobs 1918). However, the time of exposure would then become more critical. The upstream migrant would in all cases experience a slow rise in temperature within or below the lined channel. Based on the diurnal behavior patterns of the Hawaiian gobioids as observed in field and laboratory, it seems unlikely that migration would be restricted to the nocturnal period, even as a means of avoiding thermal stress.

Hoar (1953) found that positive rheotaxis in salmon fry decreased with increasing temperature to a point of negative rheotaxis. It was suggested

that this might aid in the initiation of downstream runs as temperatures rose in spring and early summer. For the Hawaiian goby fry, the point of negative rheotaxis would be a point of high stress dependent on the magnitude and duration of the stressor. The length of the lined channel section in which the heating occurs would determine the duration of exposure, and is thus critical to all migration.

Effects of Sub-lethal Temperatures: Growth

The theoretical responses of growth to temperature elevations are 1) initial increased growth with temperature up to a level for "optimal" growth; 2) decreased growth with further temperature increase down to a level of zero growth; 3) shrinkage occurring within a small temperature range, until 4) death (Gibbons 1976). Stages 1, 2 and 4 were observed in the responses of the three gobiids to different fluctuating thermal regimes. Growth appears to decrease with increasing temperature above 30°C for Awaous stamineus and 32°C for A. genivittatus. The maximum growth rate for Lentipes concolor is likely to be found at some temperature below 30°C. Results from a continuum of thermal regimes would define the relationships in detail, but such an extensive investigation was beyond the scope of this work.

The temperatures for "optimal" (i.e. most rapid) growth were approximately 7-8°C below upper lethal limits for each species. No general statement can be made concerning the deleterious effects of rapid growth. Ferens and Murphy (1974) found larger mosquito fishes in the cooler areas of a pond than in the warmer areas, suggesting that the growth rate differential due to high temperatures is only a temporary phenomenon. In temperate regions, high water temperatures could encourage feeding during winter months and result in the attainment of a larger than normal size. This would not be possible in a tropical climate. Andrews and Stickney (1972) found that growth in channel catfish increased with temperature to 30°C but fell off at 34°C. They showed that temperatures which elicit rapid weight gain also elicit higher lipid content and thus abnormal body composition. In this study, in which food was non-limiting, rapid growth at high temperatures may have been due primarily to high consumption and rapid digestion (Clark 1969).

Standard deviation about the mean weights changed with increased temperature in the same manner as did mean weight. While it is to be expected that standard deviation will increase with the mean, normalized standard deviations, SD/\bar{X} , showed trends similar to standard deviations alone. Increase in standard deviation could be interpreted as increase in individual variability in response to temperature within the sample. The point of peak standard deviation would represent the beginning of a common species response to stress.

This study has shown that conditions which would prove fatal to at least four species of native organisms exist in some altered streams containing lined channels. The number of species increases when the effect of prolonged exposure to sub-lethal temperatures during cooling is

considered. If the temperatures for optimum growth are indeed around 7 or 8°C below the lethal limits determined, then potentially harmful conditions may exist for more species and in less severely degraded streams during the dry season. The overall situation would likely be shown to be more critical if the effect of elevated temperatures on early life stages and reproductive behavior were investigated. It has been generally established that, just as the thermal range for growth is narrower than that for activity, ranges continue to narrow as embryo survival and spawning parameters are considered (Brungs 1971; Fry 1967; U.S.E.P.A. 1976).

Shelter

Laboratory and field observations suggest that native species are dependent to some degree on shelter. Lentipes concolor, Sicydium stimpsoni, Neritina granosa and Atya bisulcata are commonly found in riffles, which are micro-habitats whose existence implies considerable bottom heterogeneity. With the exception of Awaous genivittatus and Eleotris sandwicensis from the lower stream reaches, the fauna shows strong orientation to rocks and boulders which dominate the natural substrate.

Despite this apparent attraction to shelter, little physiological stress was demonstrated to result from long-term exposures to unsheltered laboratory test conditions. Studies on predation were not feasible here, but lack of shelter would likely increase the susceptibility of post-larval forms to predation, e.g. from Eleotris sandwicensis and the introduced Tahitian prawn, Macrobrachium lar. Shelter loss resulting from lined channel and culvert construction appears to have two general effects. It aids in making the immediate bottom environment so unattractive to native fauna that few can be expected to be found there (Norton et al. 1978). Total available habitat within the stream is thus reduced. Lack of shelter also increases the vulnerability of upstream migrants to high flow, because all objects capable of producing eddies or regions of calm water have been eliminated.

SUMMARY AND CONCLUSIONS

The effects of channelization on certain aquatic biota are well documented. The data required, however, for improving construction designs so as to minimize the biological impact are seldom sought (Karr and Schlosser 1978). This study focused on those morphological variables which influence thermal variability to the immediate and long-term survival of native macrofauna.

Temperature, pH, conductivity and dissolved oxygen in altered streams exceeded levels in unaltered streams during the day, but 24-hour sampling showed that nighttime minima were generally similar. Lack of shelter in concrete lined channels make them unsuitable habitat for native organisms and more difficult to traverse during migrations. Significant channelization effects on turbidity appeared to be limited to increases during the construction phase. Norton et al. (1978) showed that the percentage of native organisms inhabiting a natural bottom channel was significantly lower in streams containing lined channels and other forms of channelization than in unaltered streams.

Temperature elevation was correlated with the amount of insolation reaching stream water in natural and altered channels; thus heating was high where shade cover was low. Extreme heating in lined channels appeared to also be the result of shallow water depths, focusing of solar radiation by vertical walls, and high heat transfer in concrete. Recorded temperatures in lined channels were shown to be above the lethal limits of several native species. Conditions in less extensively degraded stream sections were shown to be capable of long-term metabolic effects on growth and probably reproduction.

The secondary effects of temperature and its synergistic involvement with other water parameters were not considered. However, Holland et al. (1974) suggest that the directional selection imposed by two or more stressors acting simultaneously may be most critical to organisms. The domination of communities in altered streams by the introduced fauna suggests that a major effect of channelization involves the presence of exotics. Darwin has emphasized that species are likely "limited in their ranges by the competition of other organic beings quite as much as, or more than, by adaptation to particular climates" (Darwin 1859, p. 140). The next step in the consideration of the decline of Hawaiian endemics should be an investigation into the competitive and predatory interactions between indigenous and introduced species.

Future modification of stream channels should be avoided where possible. The construction of artificial bank and bed structures, as in lined channels, can be considered the most damaging type of alteration. The wall revetment type of modification appears to have less overall impact on physicochemical variability and the biota than the vertical concrete walls and smooth bottom of the lined channel. In both cases, however, the removal of nearstream shade vegetation is the major cause of stream temperature elevation.

Lined channel sections should be kept short, and unaltered sections should be provided immediately downstream. These areas would serve as buffer zones where temperature would be allowed to decrease, and they would significantly lower the amount of time an organism would be required to spend in a lined channel during migration. Lined channels should be constructed with narrower, perhaps V-shaped notches in the bottom at mid-channel or with slanting bottoms, so as to provide greater water depth during low flow conditions. Smooth concrete bottoms should be replaced by irregular bottoms, perhaps containing structures designed to provide shelter. A concrete lined channel presently under construction in Iao Stream on Maui contains such a "rough" bottom. Mitigation in presently channelized streams should include revegetation of stream banks to increase or reestablish an overhead canopy.

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Appendix A. Weight vs. Length Relationship for Three Species of Gobiid Fishes Used in Growth Experiment Analysis

Lengths and weights of specimens in samples of Awaous genivittatus, A. stamineus and Lentipes concolor were recorded. The Awaous individuals were collected at Nuuanu Stream in Honolulu. All Awaous used in the growth experimental series were also collected at this site. Data for Lentipes concolor came from the individuals utilized in growth series 6C, which were collected on East Maui.

For each species, lengths and weights were fitted to the power curve,

$$\text{Weight} = a \cdot \text{Length}^N,$$

using the Hewlett-Packard HP-67 Programmable Pocket Calculator program SD-03A. Values for a , N and r^2 (coefficient of determination) for the three species are shown below:

Species	a	N	r^2
<u>A. genivittatus</u>	1.74×10^{-6}	3.43	.99
<u>A. stamineus</u>	6.55×10^{-8}	4.63	.66
<u>L. concolor</u>	1.43×10^{-6}	3.47	.93

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